Proceedings of the Canadian Society for Mechanical Engineering International Congress
32nd Annual Conference of the Computational Fluid Dynamics Society of Canada
Canadian Society of Rheology Symposium
CSME-CFDSC-CSR 2025
May 25–28, 2025, Montréal, Québec, Canada

Development of a bladder flow simulator for visualizing ureteral jet dynamics

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Abstract

Ultrasound imaging of ureteral jets provides valuable insights into urogenital health, but its diagnostic capabilities remain limited. The unilateral absence of a ureteral jet often indicates ureteral obstruction, however recent studies also suggest correlations between jet characteristics and conditions such as non-obstructive renal stones, urinary tract infections and other pathologies. Nevertheless, significant variability among patients limits diagnostic reliability. To address these challenges, we developed a physiologically-accurate *in vitro* simulator of the bladder flow environment, offering a controlled platform for studying ureteral jet dynamics under various pathological conditions.

The design of the simulator draws inspiration from existing cardiovascular flow simulators and is divided into three critical components. The first is the development of a bladder model that closely approximates human anatomy. The second is the activation system, which provides precise control over ureteral jet characteristics using high-precision linear motors. The third is the instrumentation system, enabling data collection through ultrasound imaging, particle image velocimetry (PIV) and pressure sensors for real-time analysis.

The bladder is modelled as an ellipsoid with average human bladder dimensions and anatomically-accurate placements of the ureterovesical junctions and the urethra. A transparent silicone rubber mold, with elastic modulus similar to that of a human bladder, is created from a soluble 3D-printed polyvinyl alcohol (PVA) model. Two high-precision linear motors reproduce the ureteral jets with independently controlled pulses. These motors provide a positional accuracy of 50 μm and, when paired with selected syringes, achieve a ureteral jet volume accuracy of ~5 μL and physiological jet velocities of 50-100 cm/s. Precise motor control allows modulation of jet characteristics, duration, frequency and waveform (monophasic and polyphasic). A hemostasis valve integrated into the urethra provides access for a pressure probe to monitor bladder pressure. The entire system is housed in a transparent plexiglass enclosure, enabling real-time visualization of fluid dynamics through ultrasound modalities and PIV.

The *in vitro* bladder flow simulator is the first to replicate the bladder flow environment with high physiological detail including realistic ureteral jet patterns. Moreover, comprehensive visualization and systematic analysis of bladder flow dynamics is made possible beyond basic ultrasound observations of the ureteral jets. This simulator offers an interesting platform to gain new insights into how various urogenital conditions disrupt normal bladder flow patterns. Its ability to model a wide array of characteristics is expected to enhance our understanding of the coupling between bladder flow and urogenital conditions, and may lead to new diagnostic strategies.