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Lower Urinary Tract Symptoms Diagnosis by Uropine: A MEMS based economic urodynamic system

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Abstract

Lower urinary tract symptoms, or LUTS, are a major and common urological burden that impacts a wide range of people of all ages and genders. Two potential causes of LUTS are neurogenic bladder dysfunction and benign prostatic hyperplasia (BPH) [1]. Urodynamic study (UDS), a functional evaluation of bladder and urethra, is a standard diagnostic procedure for these conditions[2]. However, high cost, lack of portability, and operational complexity of multi-lumen catheterization and laborious fluid-filled pressure transmission lines are characteristics of conventional urodynamic instrumentation[2][3]. These restrictions significantly limit urological care accessibility, especially in rural and resource-constrained settings. Thorough hardware design, engineering process, and clinical validation of "Uropine," a novel, inexpensive, AI-powered portable biomedical device intended to upend a established paradigm of LUTS diagnosis, are described in this research paper.

Uropine system provides real-time, high-fidelity monitoring of intra-vesical pressure (IBP) and intra-abdominal pressure (IAP) by combining sophisticated Micro-Electro-Mechanical Systems (MEMS) pressure transduction technology with an easy-to-use single-catheter interface. This report provides a thorough technical analysis of hardware subsystems of a device, covering topics such as implementation of embedded microcontroller-based data acquisition, design of high-precision analog signal conditioning circuits using instrumentation amplifiers, and physics of piezoresistive sensing elements. This study establishes Uropine as a feasible, scalable hardware platform that can provide tertiary-grade diagnostic precision in a portable form factor by combining theoretical biomedical engineering principles with empirical clinical data.

Introduction

1. The Clinical Engineering Landscape of Urodynamics

In order to diagnose urinary system dysfunction, urology, a specialty area of medicine, mainly uses physiological parameter measurements. Urine is stored at low pressure and expelled at high pressure by the Lower Urinary Tract (LUT), a complex hydro-mechanical system made up of bladder, urethra, prostate, and sphincter mechanisms as shown in Figure 1 [2]. LUTS, a collective term for storage symptoms (urgency, nocturia, incontinence), voiding symptoms (hesitancy, slow stream, intermittency), and post-micturition symptoms (incomplete emptying), is caused by disruptions to this system.

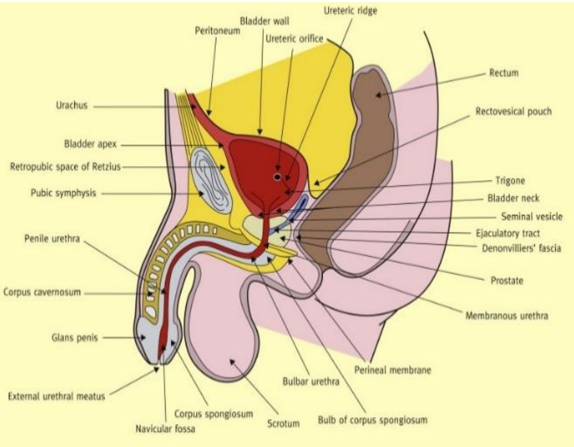

Figure 1 Anatomy of the Lower Urinary Tract[4]

The accurate measurement of the bladder's pressure-volume relationships is necessary for the diagnosis of these conditions. Cystometry, a part of urodynamic studies where bladder is filled with fluid and pressure sensor records the intra-vesical pressure response, is a traditional method for doing this. The engineering challenge is to precisely translate the biological pressure, which normally falls between 0 and 100 cmH_2O, into a comprehensible electrical signal while eliminating artifacts brought on by electronic noise, hydrostatic pressure heads, and abdominal movement.

For urodynamics, conventional hardware solutions are basically fixed labs. They employ strain-gauge transducers that are connected to the patient via long, fluid-filled catheters and fastened to external stands. These devices use a continuous fluid column to transfer bladder pressure to an external sensor. These systems are limited by their physical size, even though they are accurate when properly calibrated. They need both urethral and rectal catheterization in order to measure abdominal pressure. Additionally, "knocking" artifacts and air bubbles in the fluid lines are common. Furthermore, the majority of people in developing nations cannot afford this equipment due to its high cost, which leads to severe disparities in access to healthcare.

2. The Uropine Proposition: A Hardware Paradigm Shift

In order to address these persistent issues, the Uropine project redesigns the urodynamic hardware. It switches to a compact, solid-state technique using MEMS technology from external, fluid-coupled transduction [5]. The device is now smaller and less expensive. The bill of materials (BOM) cost for clinical towers is estimated to be around 10,000 INR, a significant decrease from lakhs of rupees [6].

Three fundamental engineering pillars serve as the foundation for this hardware innovation:

1. MEMS miniaturization: By substituting silicon-based strain gauges for macro-scale ones Micro-Electro-Mechanical Systems (MEMS) sensors, high-sensitivity pressure It is made possible to measure in a package that is compact enough to be incorporated into a wearable or portable device[5].
2. Simplified Interface: By reducing patient discomfort and the setup's mechanical complexity, a "single-catheter" design challenges the conventional requirement for simultaneous multi-site measurement using serial or algorithmic questioning techniques [7].
3. Embedded Intelligence: By incorporating a microcontroller-based processing unit, real-time digitization and AI analysis are made possible at the edge. This eliminates the need for external server racks by turning unprocessed sensor data into diagnostic insights [8].

3. Objectives and Scope of the Report

This study provides comprehensive technical documentation of the hardware implementation of the Uropine device. Beyond a basic functional overview, the decisions made at the circuit and component levels that enable the device to function are examined. Included in the focus are:

- **Sensor Physics:** An in-depth examination of piezoresistive MEMS sensors' "beam-membrane-island" structures and their potential applications for physiological pressure readings between -5 and 150 cmH_2O.
- **Analog Signal Chain:** An analysis of the circuitry for signal conditioning with an emphasis on how Instrumentation Amplifiers (IAs) maintain a high Common Mode Rejection Ratio (CMRR) while amplifying microvolt-level sensor outputs.
- **Digital Architecture:** An analysis of the study's "Algorithm for Hardware Analog-to-digital converter (ADC) requirements,

MCU selection, and implementation.
- **Clinical Validation:** Real-world cystometrogram data from various patient case studies are compared with the hardware's performance characteristics, such as linearity, hysteresis, and noise floor.

This report intends to serve as a reference for the upcoming generation of portable, reasonably priced biomedical instruments by outlining these features.

Theoretical Framework: Physics of Urodynamic Hardware

1. The Hydrodynamics of the Lower Urinary Tract

When designing hardware for LUTS diagnosis, it is essential to comprehend the physical parameters being measured. The bladder is a kind of viscoelastic reservoir [9]. The intra-vesical pressure (P_{ves}) stays comparatively low as the bladder fills because the bladder wall can stretch.

- **Normal Physiology:** 10 to 15 cmH_2O is the average resting pressure [10].
- **Pathophysiology:** Pressure can rise dramatically during voiding or when the detrusor is hyperactive. "High voiding pressure" refers to a pressure greater than 50 cmH_2O. When neurogenic bladder or outlet obstruction occurs, pressures can rise to 80–100 cmH_2O. Vesicoureteral reflux and kidney damage are increased by this [10].

In order to avoid maxing out at high pressures (up to 200 cmH_2O), the hardware should be able to function with a large amount of pressure (1-2 cmH_2O). Because P_{ves} is the total of the transmitted abdominal pressure (P_{abd}) and the pressure produced by the detrusor muscle (P_{det}), IAP measurement is also quick [7]. While P_{abd} is measured independently using a rectal catheter in conventional systems [3][11], the Uropine method, which uses a single catheter and analyzes "pressure shifts" during movement, suggests a hardware possibility of detecting composite pressure changes and potentially isolating components through signal morphology analysis.

2. Transduction Technologies: A Comparative Analysis

The development of urodynamic hardware is defined by the pressure transduction technique [2].

Fluid-Filled Systems (Historical Standard)

- These devices use a saline column to transmit bladder pressure to an external transducer [3].
- **Physics:** The system exhibits the characteristics of a second-order underdamped oscillator. The mass of the fluid and the tubing's compliance determine the frequency response [12].
- **Hardware Issues:** Hardware problems include damping from air bubbles acting as capacitors in the hydraulic circuit, absorbing pressure energy, and "whipping" (artifacts from catheter movement). The transducer must be precisely level with the patient's bladder because hydrostatic offset is a significant problem [12].

Air-Charged Systems (Modern Clinical)

The catheter tip of devices such as the T-DOC is equipped with an air-filled balloon.

- **Physics:** The overdamped frequency response is caused by the compressibility of air [12].
- **Hardware Advantage:** They are less susceptible to movement artifacts and immune to hydrostatic pressure differences (height of the sensor vs. bladder doesn't matter). Nevertheless, the disposable catheters are costly.

MEMS-Based Systems (Uropine Approach)

Solid-state MEMS technology is used in uropine.

- **Physics:** When pressure is applied, a silicon diaphragm with implanted piezo resistors deflects [5][13].
- **Hardware Advantage:** High natural frequency (kHz range), minimal hysteresis, and miniaturization are hardware advantages. Uropine combines the responsiveness of solid-state sensors with the affordability of external electronics by positioning the MEMS sensor either at the catheter tip (implantable style) or very close to the patient (portable module) [5][6].

3. MEMS Sensor Physics

The Piezoresistive Pressure Sensor is probably the particular class of sensors used in uropine.

- **Piezoresistive Effect:** When a semiconductor crystal (silicon) experiences stress, the mobility of charge carriers is altered, which modifies electrical resistivity.
- **Wheatstone Bridge:** A bridge-shaped arrangement of four piezo resistors is placed on the diaphragm. Two resistors are positioned in compressive stress areas and two in tensile stress areas. This differential configuration offers first-order temperature compensation and optimizes sensitivity (S) [13].

- **Beam-Membrane-Island:** A central rigid island suspended by thin beams on the membrane is used in advanced designs reported in the literature (Han et al., 2023). Compared to flat diaphragms, this structure greatly increases sensitivity for low-pressure biomedical applications by concentrating mechanical stress on the beams (where resistors are located) [14].

System Architecture and Component Selection

A fluidic interface and integrated electronic components are features of the hybrid Uropine hardware. Medical pressure transducers, amplifiers, PCB boards, displays, and resistors are listed as necessary components in the "Components Needed" section of the original study. We will now go into more detail about each's technical requirements and design justification.

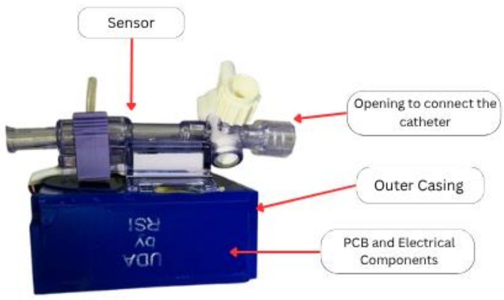

Figure 2 Uropine device – front view

Figure 3 Uropine device – side view

1. The Sensing Subsystem: MEMS Pressure Transducer

Sensor Selection Criteria

The sensor needs to adhere to certain biomedical requirements in order to properly diagnose LUTS:

- **Pressure Range:** 0 to 200 cmH_2O, or roughly 0 to 20 kPa or 0 to 3 psi [10].
- **Overpressure Tolerance:** Must endure unintentional spikes of at least three times the full scale (such as coughing or flushing a catheter).
- **Media Compatibility:** If a fluid-filled coupling is used, the sensor interface must be able to withstand exposure to saline or moisture.
- **Cost:** Since the project is expected to cost close to 10,000 INR in total, mass-produced commercial-off-the-shelf (COTS) sensors must be used instead of specially made medical-grade silicon dies.

The MPS20N0040D or comparable DIP-packaged piezoresistive gauge pressure sensors are very likely candidates or functional equivalents given these limitations and the "low-cost" requirement. These sensors are ideal for the voiding pressure range because they usually have a range of 0–40 kPa (roughly 0–400 cmH_2O) [5][15][16].

Sensor Integration

The PCB is put inside a casing to cover the electrical systems, and the sensor has been installed on top of it. Medical-grade tubing is used to attach the catheter to the opened port of the sensor as outlined in the Figure 2. The pneumatic/hydraulic interface is created by this coupling [17].

- **Mechanism:** When the bladder contracts, pressure is transferred to the air/fluid column through the catheter lumen, applying force to the MEMS diaphragm.
- **Design Consideration:** A hydrophobic filter or a flexible isolation membrane is frequently positioned in the path to prevent urine from contaminating the electronics, or the system makes use of an air-charged interface in which only air reaches the sensor and the catheter contains a balloon. For ease of use and cost-effectiveness, the Uropine text suggests an air-column approach or a fluid-filled line with a meniscus barrier [2][11].

2. The Digital Core: Microcontroller Implementation.

Microcontroller Unit (MCU)

An app can receive "real-time data" from the "AI-powered" device.

- **Selection:** The most popular choices for reasonably priced IoT biomedical devices are the **ESP32** and **ESP8266** series. Their dual-core architecture allows one core to handle ADC sampling for sensor data acquisition, while the other core takes care of Bluetooth and Wi-Fi connectivity as well as simple AI inference tasks.
- **ADC Interface:** The amplified analog

signal is fed into the analog-to-digital converter of the MCU. While the ESP32 has an internal 12-bit ADC, biomedical precision often demands an external 16-bit or 24-bit ADC to resolve minute pressure changes (<1 cmH_2O) without quantization error. The "high voiding pressure" of 50+ cmH_2O must be digitized with enough resolution to also see the small 10-15 cmH_2O resting pressure clearly.

- **Data Transmission Port:** The open port (as shown in Figure 3) of microcontroller used in the device relates to the display device for transmission of the data via serial port.

Algorithm for Hardware Implementation

Referring to the "Algorithm for hardware implementation" (Figure 4 in source context), the firmware flow typically involves:

1. **Initialization:** Power-on, microcontroller and peripherals initialized.
2. **Patient Interface:** Ensure device is connected to the patient and signal readiness.
3. **Data acquisition:** Begin pressure signal acquisition through catheter in continuous reading mode.
4. **Data measurement:** Start real-time pressure measurement.
5. **Internal sensor processing:** Apply baseline correction using atmospheric pressure.
6. **Transmission:** Data packetization for the Uropine App's WiFi and serial port transfer.
7. **Report generation:** Generation of report from the acquired data in the Uropine App.

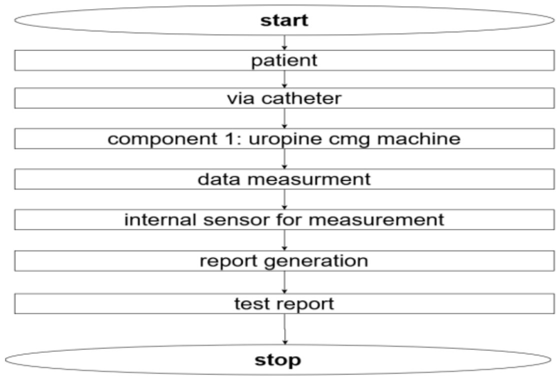

Figure 4 Flowchart for real-time pressure acquisition and processing

3. Power and Packaging

Figure 5 Compact and pocketable machine

Portability: The gadget allows patients to move around freely and is small enough to fit in a pocket or tie around their waist to ensure keeping the location at the bladder level as demonstrated in Figure 5.

Table 1 summarizes the hardware specifications derived from the design requirements:

Table 1: Summary of the hardware specifications

Subsystem	Component Type	Specification / Function	Comparison to Standard
Sensing	MEMS Piezoresistive	Range: 0-40 kPa (0-400 cmH_2O) Sensitivity: ~2-5 mV/kPa	Replaces external strain gauges; lower cost, higher durability.
Interface	Single Catheter	Material: Silicone/Latex Size: 6-8 Fr	Reduces invasiveness compared to dual-lumen standard catheters.
Conditioning	Instrumentation Amp	Gain: 100-150 V/V CMRR: >100 dB	Replaces bulky rack-mounted amplifiers.
Processing	Microcontroller (ESP32)	Connectivity: Wi-Fi and wired via serial port ADC: 12-bit or ext. 24-bit	Replaces PC-based data acquisition cards.

Experimental Validation and Hardware Performance

Clinical trials were conducted with patients to verify the efficacy of the hardware design. Cystometrograms, or pressure-time plots (shown in Figure 6), are used to display the results. They offer convincing proof of the functionality of the hardware [18].

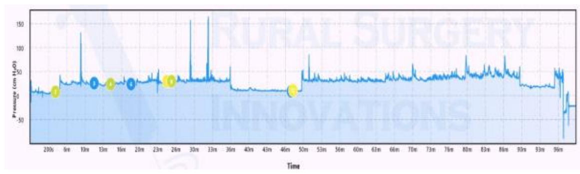

Figure 6 Pressure–time response captured by Uropine hardware

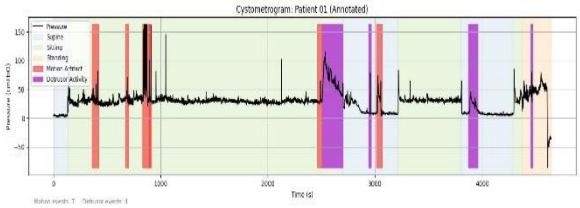

Figure 7 Cystometrogram generated by Uropine device

1. Sensitivity and Resolution Validation

- **Low-Pressure Detection:** The device could identify between 10 and 15 cmH_2O, but Patient 6's resting bladder pressure was 12 cmH_2O. Physiological signals can be distinguished from background noise at low pressures thanks to the sensor and amplifier chain's high Signal-to-Noise Ratio (SNR). This ability is demonstrated by its recognition of the "Light green bubble," which indicates "initial sensation" at about 28 cmH_2O [10][18].
- **Positional Sensitivity:** Changes in posture caused pressure shifts to be detected by the device. For example, when the "Yellow bubble" moves from a lying down to a sitting position, the pressure increases by about 66 cmH_2O. This hydrostatic shift, which is typically between 10 and 20 cmH_2O, supports the temperature compensation mechanisms of the piezoresistive bridge. It requires a system with minimal drift and strong DC stability.

2. Dynamic Range and Linearity

- **High-Pressure Capabilities:** The pressures measured by Patients 8 and 11 were 101 cmH_2O and 99 cmH_2O, respectively. These numbers indicate high voiding pressures, which are often seen in obstructive diseases.
- **Conclusion:** At these high levels, the hardware was not at its limit. This demonstrates that the amplifier gain was appropriately computed to cover the 0 to 150 cmH_2O range within the input voltage limits of the ADC, such as 3.3V. The MEMS sensor functions well within its linear elastic region if it responds linearly over this large range, from 12 to 101 cmH_2O.

3. Temporal Response and Artifact Rejection

- **Event Capture:** The cystometrograms show clear pressure spikes (present in Figure 7). These spikes are associated with "motion artifacts" (red bar) and "detrusor activity" (purple bar).
- **Bandwidth Validation:** The system bandwidth is adequate ($>$ 10Hz) if rapid spikes can be captured. Furthermore, the hardware, or subsequently AI processing, has the temporal resolution required to analyse signal shape if it can distinguish between motion artifacts and actual detrusor contractions. Sharp rise times for artifacts and smoother contractions for muscle activity are the results of this.
- **Negative pressure artifacts:** Patient 1 reported a pressure of $-1.4 cmH_2O$. This could be a sign of a calibration error or that, in a fluid-filled system, the sensor was situated slightly above the level of the bladder. This emphasizes the need for a "zeroing" function or differential measurement capability in hardware [19].

Discussion: Engineering Challenges and Solutions

1. The Single-Catheter Challenge

The "Single Catheter" interface is the biggest hardware anomaly in Uropine..

- **Problem:** In conventional urodynamics, P_{det} (detrusor pressure) is computed by deducting P_{ves} (bladder pressure) from P_{abd} (abdominal pressure). $P_{ves} - P_{abd} = P_{det}$. Only P_{ves} is measured by a single catheter [3][11].
- **Hardware/Software Solution:** Total intra-vesical pressure (P_{ves}) is measured by the Uropine hardware, which probably used the AI component to deduce the contribution of abdominal pressure based on signal characteristics. This makes the hardware simpler (one sensor channel instead of two), but it puts a significant strain on the signal fidelity needed for the AI to work properly.

2. Cost Engineering

Making strategic component decisions was necessary to reach a price point of less than 10,000 INR.

- **MEMS vs. Optical/Implantable:** Although wireless implants and optical fiber sensors provide better biocompatibility, they are prohibitively expensive [18][20]. The main factor enabling uropine's low cost is its use of mass-market piezoresistive MEMS, which are comparable to those found in consumer electronics or automotive MAP sensors. The trade-off is that in order to guarantee medical-grade safety and accuracy, more stringent calibration and packaging are required.

3. Biocompatibility and Safety

Electrical safety for a hardware device attached to an indwelling catheter cannot be compromised.

- **Isolation:** Because uropine is battery-operated, it is naturally isolated from mains electricity, which greatly lowers the patient's risk of micro shocks.
- **Materials:** The catheter is made of standard biomedical grade latex and silicone. To avoid fluid intrusion, which could harm the electronics and possibly provide a conductive path to the patient, the sensor housing/PCB must be

protected by a sturdy enclosure [17].

Future Scope and Hardware Evolution
The foundation for upcoming developments in portable urology is laid by the current Uropine hardware.
1. **Wireless Catheter-Free Implants:** A shift toward fully implantable sensors is suggested by the literature. Subsequent versions of Uropine might further reduce the size of the PCB to produce a "bladder pill" or a catheter-tip sensor that wirelessly sends data to the external unit, doing away with the tube completely.
2. **Energy Harvesting:** Hardware integration of piezoelectric energy harvesters (powered by bladder movement) could take the place of batteries in order to prolong the operational life of portable and implantable versions.

Conclusion
The “Uropine" device is an effective example of how cutting-edge biomedical instrumentation and economical engineering can come together. The researchers have developed a practical tool for LUTS diagnosis in resource-constrained environments by reducing the enormous hardware complexity of conventional urodynamic machines into a small, MEMS-based, microcontroller-driven system. The hardware architecture, which is distinguished by its single-catheter interface, piezoresistive sensing accuracy, and embedded real-time processing, has been shown in clinical trials to provide accurate, linear, and clinically meaningful pressure data across the physiological spectrum (0–100+ cmH_2O).The disruptive potential of MEMS technology in urology is confirmed by the device's capacity to record subtle sensations, fast leakage events, and high-pressure voiding cycles with an inexpensive BOM. Such scalable hardware solutions will be crucial in democratizing access to critical diagnostic care as the prevalence of LUTS increases due to an aging global population.

References
R. C. Rosen, F. Giuliano, and C. C. Carson, “Sexual dysfunction and lower urinary tract symptoms (LUTS) associated with benign prostatic hyperplasia (BPH),” 2005, *Elsevier*. doi: 10.1016/j.eururo.2004.12.013.

F. Sempроni, V. Iacovacci, and A. Menciassi, “Bladder Monitoring Systems: State of the Art and Future Perspectives,” 2022, *IEEE*. doi: 10.1109/ACCESS.2022.3221816.

M. Cooper, P. Fletter, P. Zaszczurynski, and M. Damaser, “Comparison of air-charged and water-filled urodynamic pressure measurement catheters (Neurourology and Urodynamics (2011) 30, (329-334)),” 2011, *Wiley Online Library*. doi: 10.1002/nau.21164.

A. Mangera, A. K. Patel, and C. R. Chapple, “Anatomy of the lower urinary tract,” *Surg.*, vol. 28, no. 7, pp. 307–313, Jul. 2010, doi: 10.1016/j.mpsur.2010.03.002.

X. Han *et al.*, “Advances in high-performance MEMS pressure sensors: design, fabrication, and packaging,” 2023, *Nature Publishing Group UK London*. doi: 10.1038/s41378-023-00620-1.

D. Monshy and B. K. Jebalin, “A Mini-Invasive Bladder Urine Pressure Measurement System using IoT,” in *2nd International Conference on Sustainable Computing and Smart Systems, ICSCSS 2024 - Proceedings*, 2024, pp. 374–378. doi: 10.1109/ICSCSS60660.2024.10625358.

S. J. A. Majerus, M. Abdelhady, V. Abbaraju, J. Han, L. Brody, and M. Damaser, “Real-time wavelet processing and classifier algorithms enabling single-channel diagnosis of lower urinary tract dysfunction,” in *Machine Learning Applications in Medicine and Biology*, Springer, 2024, pp. 87–114. doi: 10.1007/978-3-031-51893-5_4.

A. Palamar, M. Palamar, and H. Osukhivska, “Real-time Health Monitoring Computer System Based on Internet of Medical Things,” in *CEUR Workshop Proceedings*, 2023, pp. 672–683.

U. E. Studer, H. Danuser, W. Hochreiter, J. P. Springer, W. H. Turner, and E. J. Zingg, “Summary of 10 years’ experience with an ileal low-pressure bladder substitute combined with an afferent tubular isoperistaltic segment,” *World J. Urol.*, vol. 14, no. 1, pp. 29–39, 1996, doi: 10.1007/BF01836342.

X. Li, B. Song, Y. Su, X. Jin, Z. Zhou, and E. Xiong, “High bladder pressure during urine storage is a main reason of upper urinary tract damage by voiding dysfunction diseases,” *Pakistan J. Med. Sci.*, vol. 28, no. 4, pp. 716–721, 2012.

T. B. McKinney, E. A. Babin, V. Ciolfi, C. R. McKinney, and N. Shah, “Comparison of water and air charged transducer catheter pressures in the evaluation of cystometrogram and voiding pressure studies,” *Neurourol. Urodyn.*, vol. 37, no. 4, pp. 1434–1440, 2018, doi: 10.1002/nau.23466.

M. Back and C. Carroll, “Principles of pressure transducers, resonance, damping and frequency response," 2023, *Elsevier*. doi: 10.1016/j.mpaic.2023.08.003.

P. Semig, C. Wells, and M. Oljaca, "Design tips for a resistive-bridge pressure sensor in industrial process-control systems," *Analog Appl. J.*, vol. 3, pp. 22–25, 2015.

X. Huang and D. Zhang, "High sensitive and linear pressure sensor for ultra-low pressure measurement," in *Procedia Engineering*, Elsevier, 2014, pp. 1202–1205. doi: 10.1016/j.proeng.2014.11.383.

M. Lv *et al.*, "Design and Optimization of MEMS Resonant Pressure Sensors with Wide Range and High Sensitivity Based on BP and NSGA-II," *Micromachines*, vol. 15, no. 4, p. 509, 2024, doi: 10.3390/mi15040509.

D. N. P. R. Jayakantha *et al.*, "Fabrication of Automated Hydrostatic Pressure-Based Densitometer with a Calibrated Pressure Sensor," *Sci*, vol. 6, no. 3, p. 41, 2024, doi: 10.3390/sci6030041.

C. C. Wang *et al.*, "A mini-invasive multi-function bladder urine pressure measurement system," in *Proceedings - IEEE International Symposium on Circuits and Systems*, IEEE, 2008, pp. 3174–3177. doi: 10.1109/ISCAS.2008.4542132.

S. Poeggel *et al.*, "Differential in vivo urodynamic measurement in a single thin catheter based on two optical fiber pressure sensors," *J. Biomed. Opt.*, vol. 20, no. 3, p. 037005, 2015, doi: 10.1117/1.jbo.20.3.037005.

B. R. Marshall, A. M. Arlen, and A. J. Kirsch, "Urodynamic catheter moisture sensor: A novel device to improve leak point pressure detection," *Neurourol. Urodyn.*, vol. 35, no. 5, pp. 647–648, 2016, doi: 10.1002/nau.22754.

Y. Zhong *et al.*, "Development of an Implantable Wireless and Batteryless Bladder Pressure Monitor System for Lower Urinary Tract Dysfunction," *IEEE J. Transl. Eng. Heal. Med.*, vol. 8, pp. 1–7, 2020, doi: 10.1109/JTEHM.2019.2943170.