# POLYMER MEMS SENSOR FOR FLOW MONITORING IN BIOMEDICAL DEVICE APPLICATIONS

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## ABSTRACT

This paper reports the application of a polymer MEMS flow sensor in sensing critical flows associated with intravenous infusions. Infusion pumps that are used to deliver drugs intravenously currently have no means of accurately sensing the velocity of fluids, thereby pump malfunctions and erroneous dosages remain undetected. The liquid crystal polymer (LCP) MEMS flow sensors presented in this work detect 'live-rates' of intravenous (IV) infusions with a threshold detection limit as low as 2 mL/hr.

## INTRODUCTION

Intravenous (IV) infusion is a most commonly practiced therapy in hospitals, which involves direct injection of liquid substances into the vein through a needle or catheter. This method of fluid infusion is conducted for many purposes, such as to maintain electrolyte balance, to preserve fluid balance deficit, blood loss, and prolonged nutritional support in bed-ridden patients. The two main methods of infusion are gravity-based infusions and infusions through peristaltic or syringe pumps. The gravity-based infusion utilizes flow obstructers like roller clamps, which are manually adjusted to regulate the infusion rate. The accuracy of such infusion is very low and the method relies to a large extent on the efficiency of the nurse. Pump infusions provide better control on infusion rates and reduce human errors. Infusion pumps use linear or rotary rollers or fingers that rotate at a certain frequency to deliver fluid at a controlled rate.

In spite of being a routine practice, IV infusion therapies have been reported to carry a higher risk and lead to severe consequences in case of an error as compared to other medical therapies [1]. Observational studies conducted in the past have shown that out of a 568 IV administrations, 69.7% of them had at least one clinical error and 25.5% of them had serious errors [1-3]. During the infusion process, it is very crucial to regularly monitor the velocity of infusion [4]. The infusion rate is a critical parameter that is prescribed depending on factors such as the type of fluid that is infused and the age of the recipient. Erroneous dosages of infusions can cause serious complications such as inflammation of the vein (phlebitis), discomfort, burning, hypersensitivity, infection etc. There have also been numerous cases of deaths and Food and Drug Administration (FDA) class I recalls that occurred due to the malfunctioning of infusion pumps. The peristaltic motions of the infusion pump also need to be calibrated over repeated use to ensure that the velocity delivered is accurate.

Currently, there are no reliable methods to accurately measure the flow velocities within IV lines. Therefore, in this paper, we present the development of an ultrasensitive polymer MEMS flow sensor that can be embedded within the IV lines to measure the live-rates of flows during the infusion. The sensor can crosscheck the velocities infused by the pump and send an alarm when the infusion velocities are beyond a certain tolerance level. The sensor could also be potentially used to send a live feedback of the velocity to the infusion pump to conduct instantaneous corrections of the pump.

## POLYMER INFUSION RATE SENSOR

### Sensing unit design

The sensing unit consists of two main parts, which are the package that allows an in-line positioning of the sensor within the IV line (Figure 1a) and the MEMS flow sensor (Figure 1b and 1c).

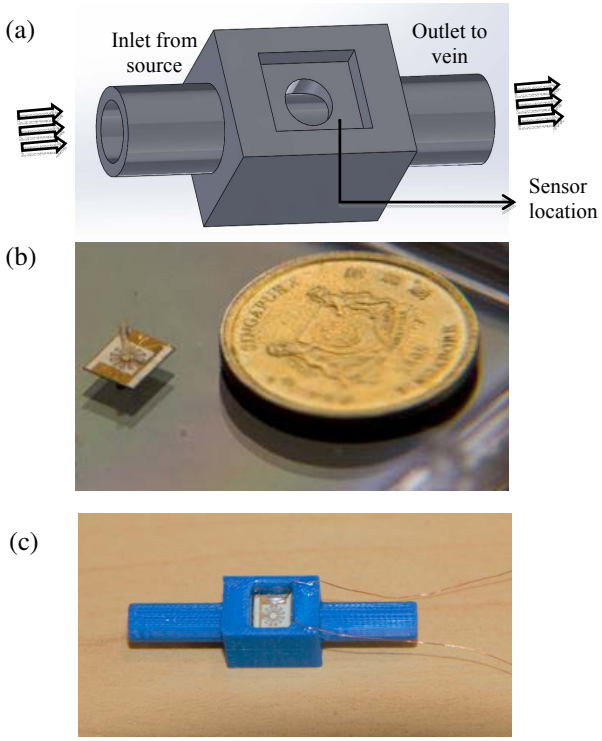


*Figure 1: Polymer MEMS flow sensor for IV infusion flow rate monitoring (a) solid works model of the package that houses the sensor and allows an in-line connection with IV line (b) MEMS flow sensor featuring a hair-like cylindrical structure beside a Singapore 5-cent coin (c) sensing unit after the assembly and wiring.*

### Fabrication and assembly of the sensing unit

In order to attain the high sensitivity desirable in measuring low flows that occur during infusions, we utilized the liquid crystal polymer (LCP) membrane sensors that were previously reported [5-8]. The sensor consists of a circular LCP membrane of diameter 2 mm and thickness 25 µm. The LCP membrane is embedded with serpentine-shaped metal strain gauges. The sensor features a high-aspect ratio hair-like structure at the center of the membrane as seen in figure 1b. The hair-like structure is a cylindrical polymer pillar that is fabricated by stereolithography. Unlike the previous design [9, 10], the cylinder is positioned on the opposite side of the membrane featuring the strain gauges. This is to ensure that the strain gauges do not come into contact with the fluid, while allowing the hair to be submerged within the fluid (Figure 2). The fixed boundary conditions of the circular LCP membrane are defined by the circular opening in the 3D printed packaging capsule shown in figure 1a. The (outer) diameter of the inlet and the outlet of the package are designed to be slightly larger than the (inner) diameter of the IV line, allowing a push-fit as well as a leak-proof in-line mounting as shown in figure 3. After the assembly of the sensor in the IV line, the IV line was connected to the bottle of saline solution and flows were generated at different velocities. No leakage of the fluid was observed at the sensing unit location.

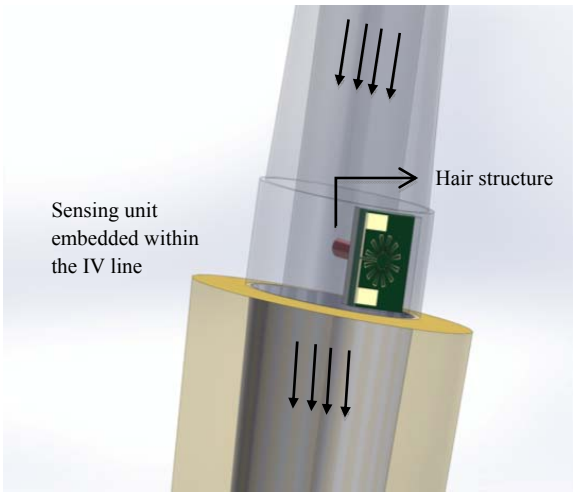


*Figure 2: Schematic describing the placement of the sensor in the IV line. The infusion fluid directly contacts the hair structure and induces drag force on it. The strain gauge and the contacts to the strain gauge do not come into contact with the fluid.*

### Sensing principle

During IV fluid infusion, as the fluid flows past the hair-like structure, it induces a drag force on the structure, causing it to bend.

Since the hair is attached to the LCP membrane at one end, the bending of the hair is transduced as a deflection of the LCP membrane due to the moment generated at the root of the pillar.

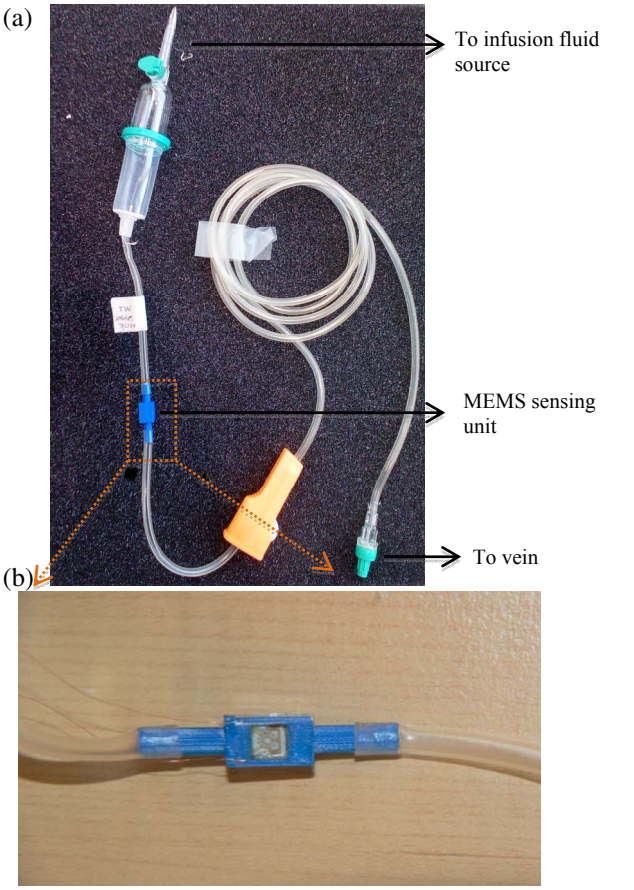


*Figure 3: IV line with the MEMS sensing unit (a) MEMS sensing unit placed in-line with the IV line through a push-fit design (b) closer view of the sensor showing the LCP membrane, the strain gauge and the wiring.*

## EXPERIMENTAL RESULTS

### Experimental setup

The IV line with the MEMS sensing unit is connected to the IV fluid chamber filled with saline solution. The IV line is connected through a commercially available clinical grade peristaltic pump. The flow rate of the fluid within the IV line can be controlled by inputting the desired velocity in the infusion pump. The MEMS sensor forms one arm of the Wheatstone bridge circuit that is assembled on an external printed circuit board (PCB) [11]. The output of the Wheatstone bridge circuit is acquired through a National Instruments Data Acquisition Card (NI-DAQ). The signals are then recorded through a LABVIEW program. The schematic in figure 4 illustrates the entire experimental setup.

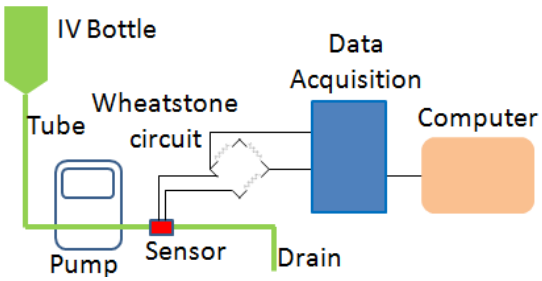


*Figure 4: A schematic of the experimental set-up showing the IV line, the infusion pump, the location of the sensor, the Wheatstone bridge circuit and the signal acquisition system.*

**Infusion flow rate sensing**

In the first experiment, blasts of flow are generated in the IV line by squeezing the drip chamber of the IV line. The sensor output is recorded while the drip chamber is gently squeezed three times. Figure 5 shows that the sensor clearly shows the response to the flows by generating corresponding three peaks. It can be seen that the sensor's output returns back to the baseline once the flow generated has stabilized.

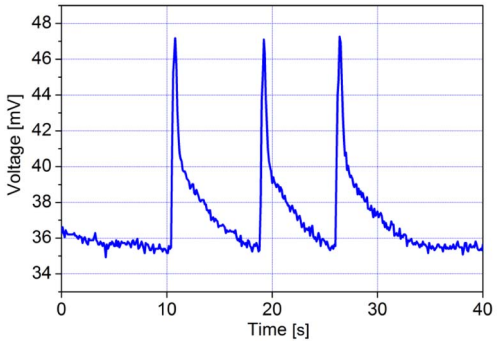


*Figure 5: The response of the MEMS flow sensor when the IV drip chamber is gently squeezed three times.*

The goal of the second experiment is to calibrate the sensor output with respect to various flow rates in the IV line. The flow velocity within the IV line is changed from a minimum of 1 mL/hr to a maximum of 50 mL/hr. The sensor output is recorded while the flow velocity in the IV line is changed from 0 mL/hr to a higher velocity. The experimental results are shown in figure 6. It can be seen that the sensor output increases with the onset of flow in the IV line. The sensor output monotonically increases with respect to the increase in the flow velocity.

It can be observed from figure 6 that the sensor is capable of measuring flow velocities as low as 2 mL/hr (which is just a few tens of drops of fluid per hour). This extremely low threshold detection limit demonstrates the high sensitivity of the sensor. An ability to measure very low flow velocities is an important factor that qualifies the sensor for use in for IV infusion flow rate sensing.

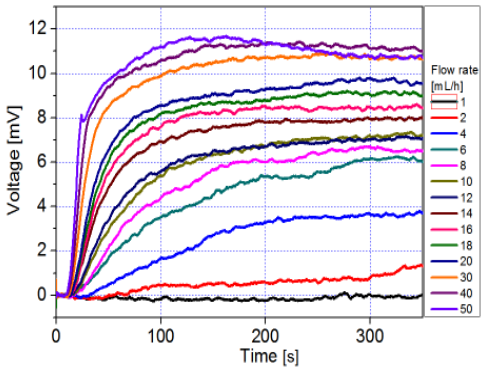


*Figure 6: Experimental results showing the flow calibrations of the MEMS sensor for infusion of saline solution*

The lowest infusion velocity that is required to keep the vein open is termed as keep vein open (KVO) velocity. The KVO velocity, for most infusion cases is roughly about 25-50 mL/hr (varies depending on many factors). The threshold detection velocity of the current sensor is 10-times below the KVO velocity suggesting a great promise in infusion flow rate sensing applications.

## OTHER BIOMEDICAL APPLICATIONS

The LCP MEMS flow sensors, due to their ability to sense low flow rates, find numerous applications in biomedical, healthcare devices and clinical appliances. Appropriate packaging of the LCP flow sensors could allow them to be integrated into biomedical robots, wearables and myoelectronic limbs etc.

The sensor, due to its low form factor, could be used as a breathalyzer to detect the breath rate and breath velocity. Wearable breathalyzers are useful in monitoring respiratory performance of sleep apnea patients, sportsmen, elderly and bed-ridden patients [12].

Another application where the sensors could deliver quintessential flow information is in the urine flow monitoring in urine drainage bags in bed-ridden patients. In hospitals, the nurses monitor several hundreds of bags at every 1-2 hr intervals [13]. Urine drainage monitoring is critical as it not only serves as a significant parameter reflecting renal function and fluid balance, but also provides a trustworthy reflection of organ perfusion and kidney state [14]. In order to measure the output, a Foley catheter is inserted through the patient's urethra until it reaches the bladder and the other end the catheter is connected to a plastic bag. The sensors could map the urine quantities in a number of drainage bags and remotely display the readings on a panel that can be observed by the hospital staff, thereby significantly reducing the nurse workload. In the future, we will extend the application of the LCP MEMS sensors for the aforementioned applications.

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