FINE-TUNING ELECTRICAL FLOW RATE SENSING IN DEFORMABLE CHANNELS

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ABSTRACT

Here we present conclusive proof that when using electrical impedance to measure volumetric flow rate in polydimethylsiloxane (PDMS) microchannels a considerable fraction of the change in impedance, due to change in flow rate, is caused by the variation in bulk solution resistance rather than the disruption of the Helmholtz double layer. The variation in solution resistance is caused, in part, by the channel deformation under pressure. Placing electrodes near the microchannel inlet produces higher sensitivity due to greater channel deformation than those at the outlet. This finding is of paramount importance for the future design of impedance-based flow sensors.

KEYWORDS: Flow sensor, Flow rate, Channel Deformation, Electrical Impedance, PDMS

INTRODUCTION

Electrical monitoring of fluid flow within a microchannel is very attractive due to its relatively ease in fabrication, compactness, integration in microchannels and their non-invasiveness measurement process [1]. To develop highly sensitive and accurate impedance-based flow sensors, it is of paramount importance to understand what are the processes occurring between the two electrodes when changing flow rate, an issue that is not been well understood.

EXPERIMENTAL

Three pairs of parallel coplanar 12.5 µm wide Ti/Au (10/90 nm) electrodes with varying gap distances (0.37 mm, 1.00 mm, 3.70 mm) were patterned on glass slides via standard lift-off processes. Microchannels (L x W x H: 45 mm x 420 µm x 28 µm) were made of PDMS by soft lithography. The plasma-oxidized microchannel was bonded to the patterned glass with the electrodes positioned perpendicular to flow direction. The volumetric flow rates of phosphate buffer saline (PBS) solution in microchannels were controlled by a syringe pump (Harvard Apparatus) [2]. The impedance between two electrodes at different flow rates were measured with a Modulab potentiostat (Solartron Analytical). The deformation of microchannels with flow rate was measured by confocal microscopy after staining the channel walls with dead red stain (LIVE/DEAD cell imaging kit, Thermo Fisher).

RESULTS AND DISCUSSION

We observed a dependence of the electrical impedance on fluid flow rate (Fig. 1a) that could not be solely due to a disruption of the Helmholtz double layer. At low frequencies (< 1 kHz), where the total impedance is governed by the electrode/solution interface impedance, there is no considerable dependence of impedance on flow rate. In contrast, the greatest flow rate dependence was observed above 1 kHz, where the solution resistance governs the total impedance. Confocal imaging (Fig. 1b) of the channel cross-section clearly indicates a significant enlargement of the channel's cross-section area as the flow rate is increase to 100 µL/min. In fact, the cross-sectional area correlated directly to the fluid flow rate with the greatest deformation observed closer to the channel inlet (P_1), where the pressure is higher. The solution resistance between two electrodes can be defined as $R = \rho \cdot L/S$, where ρ is the solution resistivity, S is the cross section area of the PDMS channel and L is the separation between the two electrodes. A greater variation in the cross section area results in a larger change in solution resistance. Consequently, impedance sensors positioned closest to the inlet (P_3) will have a greater sensitivity to flow rate than those downstream (P_4) (Fig. 1c), which is demonstrated by the sensitivity differences at P_3 and P_4. Widening the electrode gap increases the contribution of solution resistance, thus further improving the sensitivity (Figure 1d).

By separating the contribution of solution resistance (R_S) and electrode/solution interface impedance ($|Z| - R_S$) from the total impedance value (Table 1), a clear relationship between flow rate and electrode/solution interface impedance is not apparent. By contrast, the real part impedance (Z') decreases with flow rate. Moreover, this sensor demonstrates better performance when the real part of the impedance is greater than the imaginary component (i.e., the electrode/solution interface is not the dominant component of the impedance).

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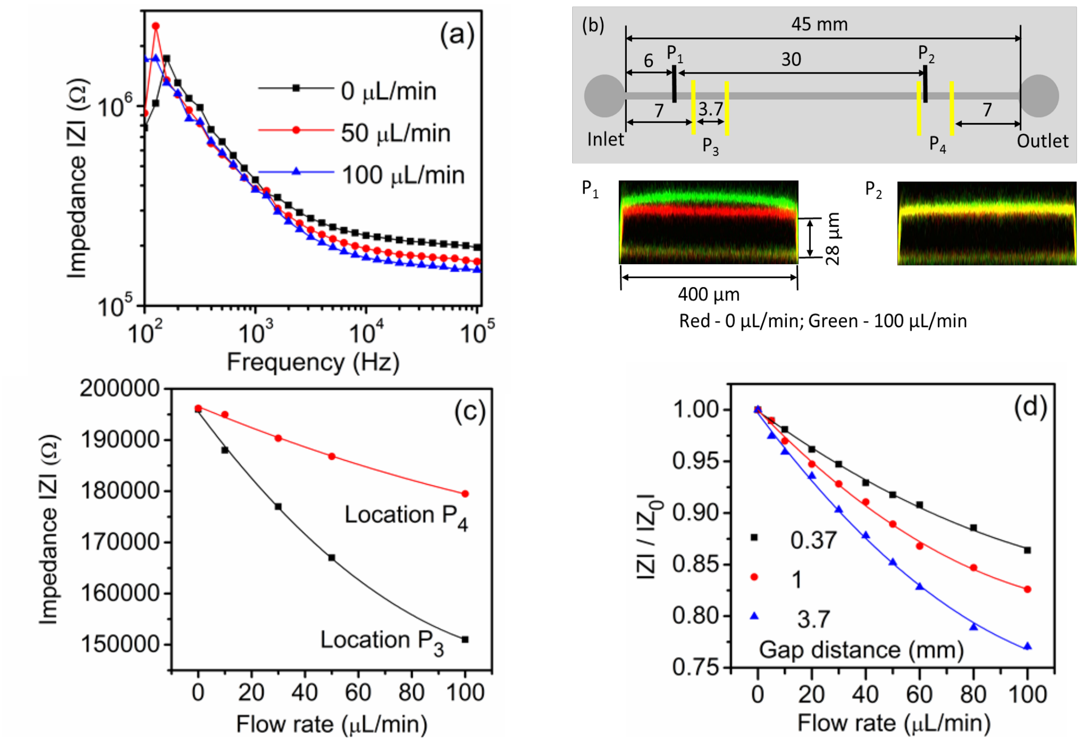

Figure 1. (a) Typical electrical impedance spectra of 1X PBS recorded on sensor design of 12.5 μm wide x 3.70 mm gap distance, positioned at location P_3 under flow rates of 0, 50 and 100 μL/min. (b) Cross section profile under 1X PBS flow rates of 0 and 100 μL/min, the aspect ratio was adjusted for presentation. (c) Influence of electrode position in the channel on sensor's sensitivity to flow rate. (d) Influence of gap distance on sensor's performance. The plotted impedance was measured at frequency of 100 kHz.

Table 1. Contribution of electrode/electrolyte interface impedance in the total impedance ($|Z|-R_S$) at various frequencies on sensor design (12.5 μm wide x 3.70 mm separation) in a 1X PBS solution (Z = kΩ, R = kΩ).

Flow rate (μL/min)	R_S solution resistance	2512 Hz				10000 Hz				100000 Hz			
		Z'	Z"	|Z|	$\|Z\|-R_S$	Z'	Z"	|Z|	$\|Z\|-R_S$	Z'	Z"	|Z|	$\|Z\|-R_S$
0	187	252	151	293	106	218	55	225	38	192	39	196	9
10	178	242	140	280	102	209	51	216	38	184	36	188	10
30	173	228	126	261	88	197	48	203	30	173	33	177	4
50	162	220	136	259	97	187	50	194	32	164	31	167	5
100	146	197	138	241	95	168	48	174	28	149	26	151	5

CONCLUSIONS

Flow derived microchannel deformation, which brings about the changes of bulk solution resistance between two electrodes, plays a decisive role in the impedance changes over flow rates. Those parameters that can increase the contribution of solution resistance, such as diluting solution concentration and widening electrode gap distance, will be critical when designing sensors with better performance.

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REFERENCES

[1] J. Collins and A. P. Lee, Microfluidic flow transducer based on the measurement of electrical admittance, *Lab chip*, 4, 7-10, 2004.
[2] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment is necessarily the best available for the purpose.

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