

Biochemical Modulation of Ionic Transport in Asymmetric Nanochannels for Label-Free Biosensing

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Summary:

Biomimetic solid-state asymmetric nanochannels serve as platforms for the integration of enzymes and functional polymers. Enzymatic reactions generate localized pH variations near the nanochannel surface, which are transduced by polymeric layers into measurable changes in iontronic current through acid–base-dependent modulation of surface charge within the multilayer assembly. The asymmetric bullet-shaped nanochannel geometry enhances the sensing response through nanoconfinement effects and amplified ionic current rectification, providing a promising strategy for the development of label-free biosensing platforms.

Keywords: Solid-state nanochannels, Ion-current rectification, Biosensing, Bioelectronics.

Background, Motivation and Objective

Nanofluidic systems based on asymmetric nanochannels have emerged as promising platforms for biosensing due to their ability to translate molecular interactions into measurable ionic current responses. Their sensing mechanism relies on the modulation of surface charge properties and ionic conductance within confined nanochannels, enabling the detection of chemical and biochemical processes without the need for molecular labeling. By integrating functional materials, we investigate the development of iontronic sensing platforms based on enzyme–polyelectrolyte-functionalized asymmetric nanochannels, where variations in the local physicochemical environment are transduced into changes in ionic current. This approach provides a versatile framework for the development of label-free biosensors for biomarker detection [1]. Current efforts focus on optimizing sensor performance, strategies toward real sample analysis are being implemented, together with improvements in fabrication and functionalization processes, to evaluate the potential of these systems for practical sensing applications.

Description of the New Method or System

The ion-track etching technique (Fig.1) provides a robust and well-established approach for the fabrication of solid-state nanochannels, and previous studies have demonstrated the proof-of-

concept of nanochannel-based biosensing approaches [2]. However, the optimization of these systems toward practical applications, including measurements in complex samples, remains a significant challenge. In this work, we report the evaluation of asymmetric nanochannel-based biosensing platforms under real and complex sample conditions. Furthermore, we are developing sample pretreatment strategies and improving fabrication protocols to enable reliable single-nanochannel-based biosensing. These advances aim to bridge the gap between fundamental iontronic sensing mechanisms and their implementation in practical analytical applications.

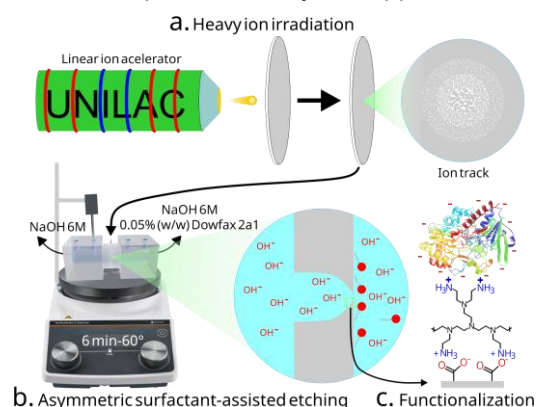


Fig. 1. Ion-track etching technology for bullet-shaped solid-state nanochannel fabrication. (a) Irradiation, (b) Wet etching, (c) Electrostatic surface modification.

Results

In this work, we present a biomimetic sensing platform based on asymmetric bullet-shaped nanochannels fabricated in polyethylene terephthalate (PET) membranes and functionalized through layer-by-layer supramolecular assembly of enzymes and poly(allylamine hydrochloride) (PAH) or polyetherimide (PEI). The cationic polyelectrolyte acts both as a structural component and as a pH-responsive transducer, converting enzyme-induced local pH variations into surface charge modulation within the nanochannel. These changes directly influence ionic transport, generating an iontronic signal that correlates with the enzymatic reaction occurring in the presence of the target analyte. The sensing strategy is applicable to different enzymatic systems capable of producing local physicochemical changes, providing a versatile framework for the detection of multiple biomarkers.

The platform was evaluated in terms of response time, pH dependence, storage stability, inter- and intra-batch reproducibility, and selectivity toward potential interfering species. In addition, sample pretreatment strategies were developed to reduce nonspecific adsorption and improve sensor performance in complex matrices. These results demonstrate the potential of enzyme-polyelectrolyte-functionalized asymmetric nanochannels as a robust and adaptable platform for label-free iontronic biosensing in practical analytical applications.

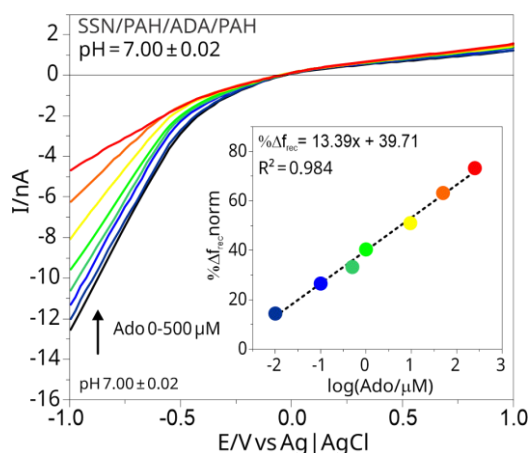


Fig. 2. Sensing performance of an adenosine deaminase (ADA)/PEI modified nanochannel to adenosine (Ado) in 10 mM KCl-0.05 mM HEPES.

The nanochannel response was quantified by the rectification factor (f_{rec}), as defined in Eq. (1,2). This parameter reflects the degree of ionic current rectification at steady state for each fixed substrate concentration (See Fig. 2).

$$\text{Eq. 1. } f_{rec} = \frac{I(-1V)}{I(1V)}$$

$$\text{Eq. 2. } \% \Delta f_{rec} \text{ norm} = \left(\frac{|f_{rec}^{initial}| - f_{rec}}{|f_{rec}^{initial}|} \right) * 100$$

To evaluate the performance of the platform in complex matrices, a simulated body fluid (SBF) containing high concentrations of BSA, ATP, and inorganic phosphate was selected as a model sample. A pretreatment and dilution strategy was implemented to minimize nonspecific interactions and matrix effects, enabling the analysis of spiked SBF samples using the functionalized nanochannel (Fig. 3).

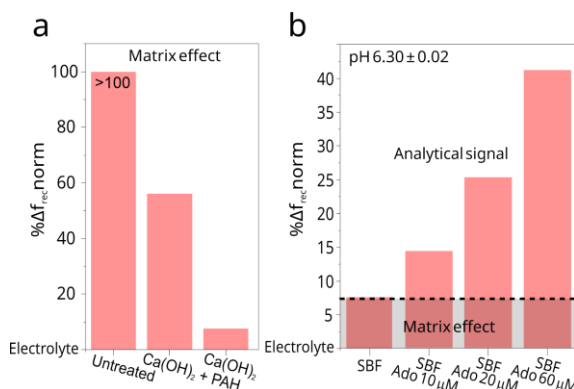


Fig. 3. Response of an ADA/PEI-functionalized nanochannel for Ado detection in SBF using 10 mM KCl and 0.05 mM HEPES as the supporting electrolyte. (a) Sample pretreatment procedure. (b) Measurement of adenosine-spiked pretreated SBF samples.

Although the matrix effect was effectively reduced by approximately 93%, it still affected the analytical performance of the system. In complex samples, the quantification limit increased and linear range decreased compared with measurements performed in electrolyte solution (Tab. 1). Nevertheless, the iontronic response of the functionalized nanochannels remained well correlated with substrate concentration in both electrolyte solution and diluted SBF, demonstrating the feasibility of the proposed sensing strategy for complex sample analysis [3].

Tab. 1: ADA/PEI-functionalized nanochannel sensing parameters.

Sample	LOQ (μM)	Linear range (μM)
Electrolyte	0.01	0.01-500
SBF	10	10 - 300

References

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