

Prevention of biofouling on iridium oxide based pH sensors using polyvinyl alcohol hydrogels

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Abstract—Metal-metal oxide based pH sensors such as, iridium oxide (IrOx) pH sensors have shown promise in monitoring pH for *in vivo* applications. In this paper, we examine the ability of PVA hydrogels in prevention of biofouling on pH sensors. This study examines the effects of biofouling on pH sensors by comparing pH sensors with and without anti-biofouling coatings made from PVA hydrogels. The results demonstrate that PVA hydrogels can be coated on the sensor surface, without affecting the sensitivity of the sensor. After coating PVA hydrogels, the rate of sensor degradation reduces without affecting the linearity of the sensor. The slope of degradation of sensitivity for the sensors coated with PVA hydrogel was 0.0038 V/pH, while it was 0.0051 V/pH without PVA coating.

Index Terms—Metal-Metal Oxide sensors, Biofouling, Polyvinyl Alcohol (PVA) hydrogels, potentiometry, pH sensor.

I. INTRODUCTION

Diabetic ketoacidosis (DKA) is a serious bodily medical disorder that occurs in type I diabetic patients and is characterised by elevated blood glucose levels and metabolic acidosis caused by ketone body accumulation in blood and urine [1]. Ketone bodies are composed of three molecules: beta-hydroxybutyrate (3-HBA), acetoacetate, and acetone, with 3-HBA being the most prevalent and significant contributor to acidosis [2]. The disorder is caused by insulin insufficiency, which results in the generation of excessive amounts of ketones as byproducts of fat breakdown [3]. The aforementioned, also known as blood acid have the capacity to function as an alternative metabolic fuel for the organism, causing acidosis when they build in the blood and urine. Despite breakthroughs in diabetes therapy, this illness is associated with substantial morbidity and mortality rates. A low blood pH in diabetes ketoacidosis (DKA) reveals metabolic acidosis induced by ketone bodies, indicating the severity of the situation and the need for rapid medical attention [4]. To avoid further physiological damage, early identification necessitates the use of an accurate pH-sensing technology [5]. The pH scale is a vital measurement for many other biological processes. Severe disturbances in acid/base homeostasis are recognised as potential complications for patients with cancer, renal failure, and psychiatric disease [6]. The intracellular fluid becomes somewhat acidic 6-8 because, for example, cancer cells prefer to convert glucose and other nutrients into lactic acid, as reported by Mani et al. Since early diagnosis is critical to preventing future physiological impairments, an efficient pH-sensing approach for tissues is required. For pH sensing, various metal oxides have been explored thus far, including

Tungsten(VI) oxide (WO_3), Ruthenium(IV) oxide (RuO_2), and Iridium Oxide (IrO_2) [7] [8]. IrO_2 is a conductive oxide that has been shown to be relatively safe for use in biological systems [9] [10]. IrO_2 has been investigated for its potential as an oxygen-evolving electrocatalyst in water electrolysis, a neuron-stimulating electrode for implanted electronics, and a pseudocapacitor for energy storage, in addition to its use in pH sensing [11] [9]. The pH sensor is a type of electrochemical cell that comprises two electrodes: the Reference Electrode (RE) and the Working Electrode (WE). [12]. A potentiostat is used to control and record the voltage of the WE and the RE. Utilising a selective enzyme makes the sensor sensitive and selective towards pH [13] [9]. The sensor converts the chemical quantity (pH concentration) into an electrical voltage, which is then measured by a readout circuit [14]. Sensor sensitivity, S , is defined as the ratio of sensor voltage change, V_s , to pH concentration change, pH :

$$S = \frac{V_s}{pH} \quad (1)$$

There are a number of factors that can alter a sensor's sensitivity. Sensitivity shifts are commonly brought on by the biofouling of sensors [15]. Accumulation of biological materials, such as bacteria, algae, or biofilms, on the detecting surfaces of pH sensors is known as biofouling of pH sensors [16]. Inaccurate pH readings can result from this buildup affecting the sensor's performance and accuracy. In this study, we will compare the drift in sensitivity of pH sensors with and without anti-biofouling coatings in the presence of biofouling. In Section II, we have described the fabrication procedure of the pH sensor, and the preparation of the anti-biofouling layer has been documented in detail. The results of the pH sensor and a detailed discussion are presented in III followed by the conclusion in Section IV.

II. METHODOLOGY

A. Sensor Fabrication

The measurements in this investigation were taken with medical-grade lancets (Hick™). The lancet's protective cap was removed and modified such that it could detect pH using enzymes in a minimally invasive manner.

B. Sensor Functionalisation

Potassium Hexachloroiridate (III) (K_3IrCl_6) from Sigma-Aldrich and all other reagents like Oxalic acid dihydrate

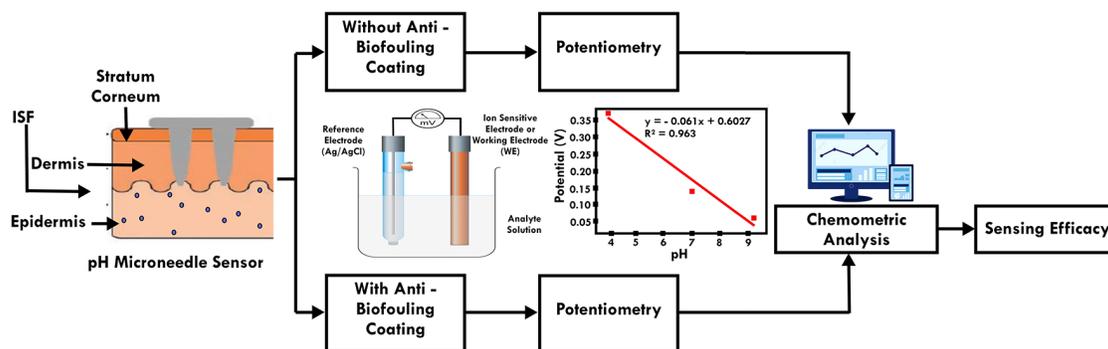


Fig. 1. This figure depicts the overall architecture of a pH sensor potentiometry analysis and its link to sensor efficacy with and without anti-biofouling coatings.

($C_2H_2O_4 \cdot 2H_2O$) and Potassium carbonate (K_2CO_3) were from Himedia and were of analytical grade.

1) *Synthesis of Iridium Oxide enzyme (IrO_2):* 2.09 mg/ml of K_3IrCl_6 , 2.9 mg/ml of ($C_2H_2O_4 \cdot 2H_2O$), and 11.05 mg/ml of (K_2CO_3) were dissolved in deionized water at 60 degrees for 1 hour, using a magnetic stirrer rotated at 800 revolutions per minute to combine the solution until it becomes transparent. After 5 to 6 hours, the solution was removed from the heat and was left in the stirrer for 24 hours until the colour changed to a light purple or blue. When not in use, the solution is kept at 4 degrees [17].

2) *Preparing of pH Solutions:* The electrochemical approaches involved a systematic increment in the pH range. The experimental conditions encompassed a pH range of 4, 7, and 9.2.

3) *Artificial Interstitial Fluid (aISF) and albumin solution preparation:* A solution was prepared by combining 2.5 mM $CaCl_2$, 3.5 mM KCl , 0.7 mM $MgSO_4$, 123 mM $NaCl$, 1.5 NaH_2PO_4 , 30 mg/ml albumin, and 7.4 mM glucose. The resulting solution was then diluted with de-ionized water [18].

4) *Deposition of Gold (Au) on the needles:* The needles were first gold-coated using an AUTO FINE COATER (Gold Sputter Coater JFC-1600) so that their features could be evaluated against those of the WE.

5) *Immobilisation of IrO_2 on gold-coated electrodes:* For the electrochemical deposition of IrO_2 onto the gold-coated Working Electrode (WE), we employed cyclic voltammetry (CV), an electrochemical deposition technique. The IrO_2 was electrodeposited by performing 21 CV scans within -0.786 V and 0.686 V at a rate of 0.1 V/s.

6) *Preparation of PVA (Polyvinyl Alcohol) film:* PVA with a molecular weight of 145000 aqueous solutions was made by heating at 95 °C with mechanical agitation for about 3 hours to achieve homogeneity. The PVA (Polyvinyl Alcohol) homogenous solutions were made by creating a 7 percent of weight/volume (w/v) solution. A hot water bath with a constant 95 degrees Celsius was maintained during the process. Following the completion of the preparation of the homogenous PVA solution, the mixture was allowed to return to room temperature [19]. Next, 10 mL of the PVA solution

was taken and combined with 50 μ L of glutaraldehyde and 50 μ L of hydrochloric (HCl) acid. Then the needles were dipped in the hydrogel solution, and it was pulled at a uniform rate [20].

7) *Instrumentation:* A potentiostat (Metrohm iStat 400s) was used for all electrochemical measurements. To begin, we applied Iridium Oxide functional groups to Working Electrodes (WE) using cyclic voltammetry (CV). The pH sensor was then calibrated using open circuit potentiometry, which provided us with a range of potential values across a wide pH range. In electrochemistry, potentiometry is utilised to measure the voltage (potential difference) between the electrodes of an electrochemical cell. It relies on the fact that the concentration of an analyte of interest correlates with the potential difference across a cell [21]. Reference electrodes, like the silver/silver chloride electrode, have a known and constant potential and are used as one of the electrodes in potentiometry. The other electrode is an ion-sensing electrode or Working Electrode (WE), which is used to make contact with the analyte. In our case, we have used Ag/AgCl as a reference electrode and an IrO_2 electrodeposited onto the gold-coated needle as a Working Electrode.

C. Degradation of Sensitivity Analysis

We have taken 2 pair of 3 needles each. The needles were first gold coated and then Iridium Oxide functional group was functionalized onto the WE. We coated one set of three needles with PVA polymer, which we are utilising as an anti-biofouling polymer, and left the other set untreated. The objective of this study is to study the impact of biofouling or sensitivity degradation on both the pair of needles with and without anti-biofouling properties (PVA polymer). Over the course of more than 2 weeks, the experiment was run. The pH values were obtained using open-circuit potentiometry. The data was collected on day one and then stored in a solution of aISF and albumin until analysis. This was done to mimic the natural environment of the dermis region, which contains proteins and ISF. The experiments were repeated every two days for a period of more than two weeks.

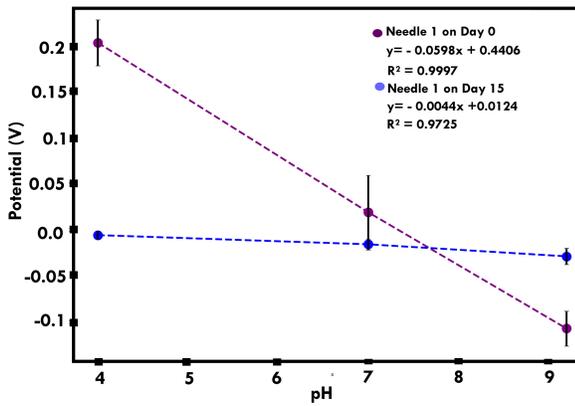


Fig. 2. This figure illustrates the potential versus pH relationship of Needle 1 coated with PVA and placed in a solution containing aISF and albumin on Days 1 and 15.

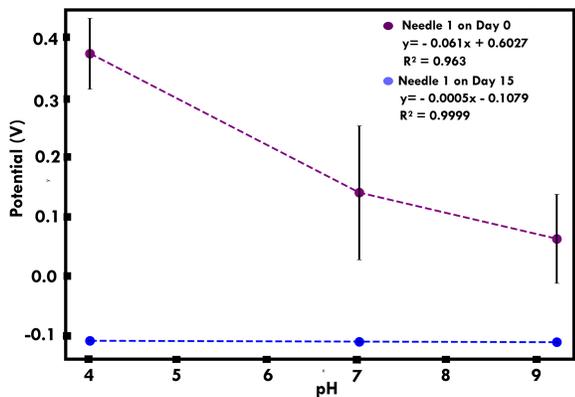


Fig. 3. This figure illustrates the open circuit potential versus pH relationship of Needle 1 without PVA coating and put in a solution containing aISF and albumin on Days 1 and 15.

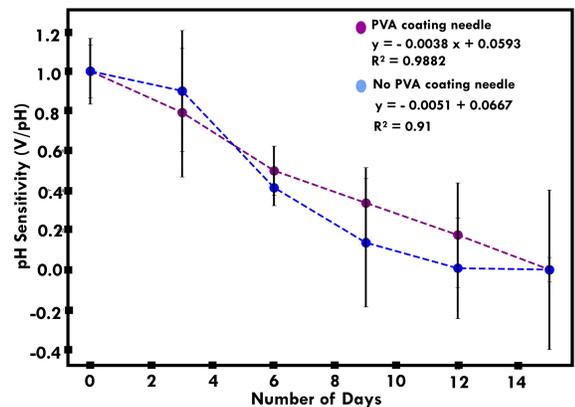


Fig. 4. The average sensitivity deterioration of a pH sensor coated with and without PVA and held in a solution containing aISF and albumin.

III. RESULTS & ANALYSIS

The pH sensor's potentiometry curve for Needle 1, with the pH scale along the x-axis and the potential for the pH scale

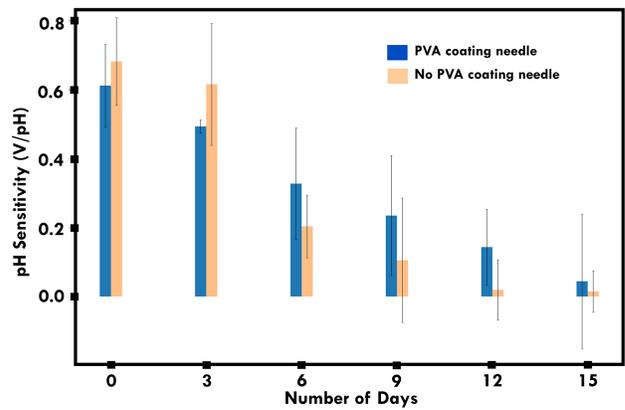


Fig. 5. A bar graph shows the average sensitivity deterioration of a pH sensor coated with and without PVA and kept in a solution with aISF and albumin.

along the y-axis, are shown in Fig 2 and Fig 3. It displays the potentiometry curve for Days 0 and 15 with and without the anti-biofoulant PVA polymer covering. The sensitivity of Needle 1 with PVA is -0.0598 V/pH on Day 0 with $R^2 = 0.9997$ and -0.0044 V/pH on Day 15 with $R^2 = 0.9725$. Also, the sensitivity of Needle 1 without PVA coating on Day 0 is -0.061 V/pH with $R^2 = 0.963$, and on Day 15 is -0.0005 V/pH with $R^2 = 0.9999$. Fig 1 depicts the overall architecture of a pH sensor potentiometry analysis and its link to sensor efficacy with and without anti-biofouling coatings. The average sensitivity degradation of the needles stored in a solution containing aISF and albumin with and without PVA coating is shown in Fig 4. The deterioration of the needles without PVA coating is seen faster than with PVA coating. The slope was found to be 0.0038 V/pH for needles with PVA coating and 0.0051 V/pH for needles without PVA coating. The statistical analysis of the average degradation of all the needles is then put in a solution containing aISF and albumin with PVA and without PVA coating is shown in Fig 5.

IV. CONCLUSION

The potential effects of biofouling on pH sensors with and without anti-biofouling coatings have been examined in this work. The pH sensor without an anti-biofouling layer was shown to be more susceptible than those with anti-biofouling. The difference in pH sensor sensitivity between those with and without anti-biofouling coatings appears to support the study of pH sensor sensitivity decline in the presence of biofouling. Without the PVA coating, there is a significant loss in sensitivity, which suggests that the biofouling agents are causing the drop in sensitivity. The study that has been presented paves the way for more research into anti-biofouling strategies to stop pH sensors from losing their sensitivity.

V. ACKNOWLEDGMENT

The authors acknowledge the Department of Science and Technology (DST), Government of India, under grant number TDP/BDTD/01/2021.

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