Monitoring Carbon Dioxide Levels in Exhaled Breath for Biomedical Applications

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Abstract. Exhaled breath analysis offers a non-invasive method for assessing respiratory health. Carbon dioxide (CO2) levels can indicate various physiologi- cal conditions, making its detection crucial in numerous biomedical applications. Such a non-invasive diagnosis is possible with a detector that utilises a pH-sen- sitive indicator that changes colour based on the CO2 concentration in exhaled breath. This colourimetric sensing element comprises a pH-sensitive polymer film containing basic or acidic groups that react with exhaled breath, causing a colour shift. The chosen dye exhibits a significant change in absorbance upon exposure to CO2, enabling its sensitive detection. As the CO2 levels rise or fall during inhalation and exhalation cycles, the indicator transitions between repre- sentative colours, allowing for breath-by-breath monitoring. This paper presents a simple and efficient method for monitoring CO2 levels in exhaled breath based on a disposable, colourimetric end-tidal CO2 (ETCO2). The rapid and reversible color change of the non-toxic indicator offers a promising tool for various bio- medical applications requiring real-time ETCO2 monitoring.

Keywords: Carbon Dioxide, ETCO2 Detection, Colourimetric Sensor, Exhaled Breath, Biomedical Applications.

1 Introduction

Endotracheal intubation (ET) is a critical skill in emergency and critical care settings, frequently performed in operating rooms, intensive care units (ICUs), emergency de- partments, and even pre-hospital environments [1]. It establishes a secure airway for patients who are unable to breathe adequately on their own, ensuring proper oxygen delivery and preventing life-threatening complications. However, confirming the proper placement of the tube within the trachea (endotracheal) and not the oesophagus (oesophagal) is crucial [2]. While methods like auscultation and chest X-rays are used, they can be time-consuming, subjective, or require radiation exposure. End-tidal carbon dioxide (ETCO2) detectors offer a more objective and rapid confirmation by detecting the presence of exhaled carbon dioxide [3]. This helps to minimise the risk of misplace- ment and the need for repeat procedures, ultimately improving patient outcomes.

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While ETCO2 detectors have significantly improved confirmation of ET placement, they can be expensive and require additional training for proper interpretation. Addi- tionally, some limitations exist, such as potential interference from ongoing cardiopul- monary resuscitation (CPR) or malfunction due to technical issues. Conventional meth- ods for measuring CO2 in breath rely on infrared detection technologies. Although these techniques provide insightful information, they are hindered by the humidity present, which permeates both breathing and surrounding air. This humidity acts as a significant source of interference, necessitating specific pre-treatment steps to minimise its impact [4]. Unfortunately, these pre-treatment procedures often drive up the cost of the equip- ment and limit its suitability for practical application in clinical settings [5]. As a result, there is a pressing need for a cost-effective, user-friendly, packed-in, and exact sensor dedicated to tracking CO2 levels in human breath.

The current aspect of CO2 analysis techniques boasts a diverse array of options [6], [7]. Among these, capnography instruments have emerged as a popular choice for CO2 measurement. With the use of infrared technology, capnographs produce a continuous plot of CO2 exhaled over time, enabling non-invasive monitoring of CO2 levels. How- ever, despite its potential for real-time feedback, the capability of capnography has not yet been fully integrated into the clinical setting due to its high cost, inconvenience, and limitations in accurately estimating lung ventilation and perfusion status [8]. To address these concerns, colourimetric CO2 detectors have emerged as a promising alternative [9]. These single-use devices utilise a pH-sensitive dye that changes colour in response to exhaled CO2. When connected to the endotracheal tube, the detector displays a clear visual cue – turning pink during expiration (indicating CO2 presence) and yellow during inspiration. This simple, rapid, and cost-effective approach offers several potential ad- vantages. Unlike conventional ETCO2 detectors, colourimetric indicators require no calibration or complex interpretation because they rely on a chemical reaction that changes colour based on the CO2 concentration, making them user-friendly even in resource-limited settings. Additionally, their visual confirmation eliminates the need for additional equipment or radiation exposure associated with chest X-rays. Although limitations like potential humidity dependence exist, colourimetric CO2 detectors pre- sent a compelling option for reliable and efficient ET confirmation in emergency and critical care settings.

2 Materials and Methods

Three indicator solutions were prepared: phenol red, neutral red, and m-cresol purple. For each solution, 0.100 g of the respective dye powder was dissolved in 2.5 ml of distilled water. Solutions were stirred for 10-15 minutes. The pH of each solution was adjusted to acidic (4), neutral (7), and basic (10) using acetic acid (CH3COOH) and sodium hydroxide (NaOH). The response time of each dye solution to exhaled CO2 was evaluated at different pH levels. Only at pH 10 did the neutral red successfully detect CO2, exhibiting a colour change from red to pink within 15 seconds. Additionally, the response time decreased with increasing CO2 concentration. Similar colour changes

were observed for m-cresol purple at pH 10, with a shift from purple to yellow in less than 10 seconds.

Polypropylene was chosen for the spun-bond nonwoven film due to being relatively cheap compared to other polymers and offering the highest fibre per kilogram yield among considered materials. This selection allows for the creation of spun-bond webs with a wide range of characteristics, from lightweight and flexible to heavy and stiff, bridging the gap between paper and woven fabrics in terms of structure. By applying a phenol-red solution on an inert substrate film and letting it dry, a thin, hydrophobic, and water-insoluble layer was created. This layer served as the base for the pH-sensitive indicator film. The pH-sensitive chemical indicator was encapsulated within a plastic housing and positioned within the gas stream between the endotracheal tube and the monitoring device as shown in Figure 1. This placement allows the indicator to change colour based on CO2 exposure. The response time of the sensor was assessed to deter- mine its ability to detect changes in CO2 concentration.

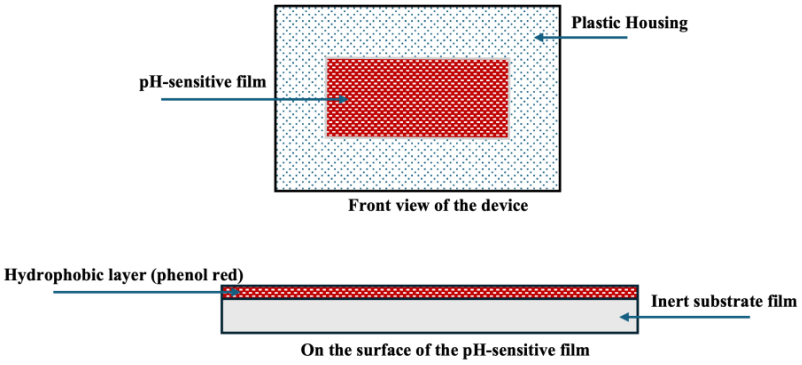

Fig. 1. Polypropylene housing.

Visible absorbance spectroscopy was employed to evaluate the pH-dependent colour changes of phenol red. Scans were performed within the visible spectrum range (380- 680 nm) on samples exhibiting a colour gradient from red (pH 7.11) to yellow (pH 4.92). These samples were prepared via serial dilution with an acidic buffer solution to achieve varying colour intensities and concentrations.

3 Results

We investigated a highly selective dye system for non-invasive CO2 detection in ex- haled breath using colourimetric indicators. The effects of pH, response time, reusabil- ity, concentration dependence, and temperature were evaluated. Dye solutions (neutral red, m-cresol purple, and phenol red) were prepared in acidic (pH 4), neutral (pH 7), and basic (pH 10) media, they exhibited a visible colour change upon CO2 addition.

The average response time for CO2 detection in phenol red was 15 seconds, decreasing with increasing CO2 concentration represented in Figure 2.

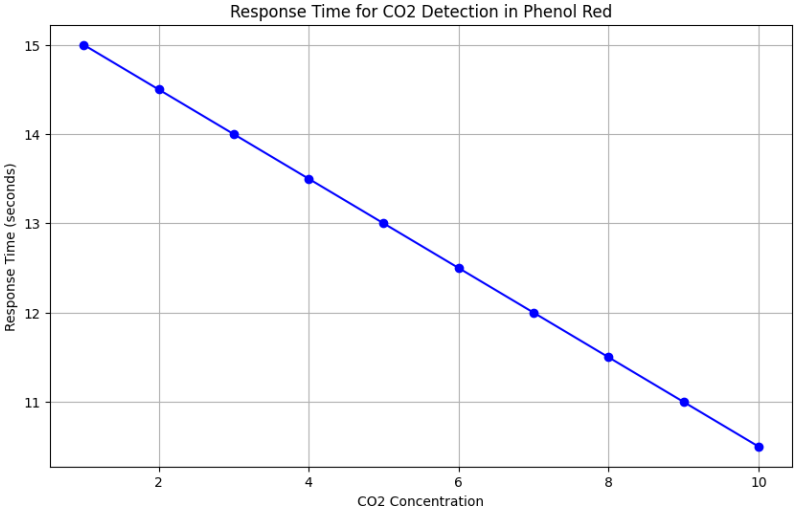

Fig. 2. Absorbance at 525nm.

The relationship between absorbance and pH was assessed using linear regression analysis. A wavelength of 525 nm yielded the strongest correlation (R^2 = 0.9321), with a root mean square error (RMSE) of 0.1973 pH, indicating a direct and highly predictable relationship between absorbance and pH at this wavelength as shown in Figure 3. Sam- ples with lower pH exhibited decreased absorbance values, potentially due to the ioni- sation of acidic functional groups and the suppression of chromophore activity in phe- nol red under acidic conditions. To assess reusability, dye solutions (including m-Cre- sol purple, neutral red, and phenol red) were heated to 50 °C after CO2 saturation. This heating step expels CO2, known to cause colour shifts. Notably, the original colours of all three dyes returned within 20-30 minutes of heating at 50 °C.

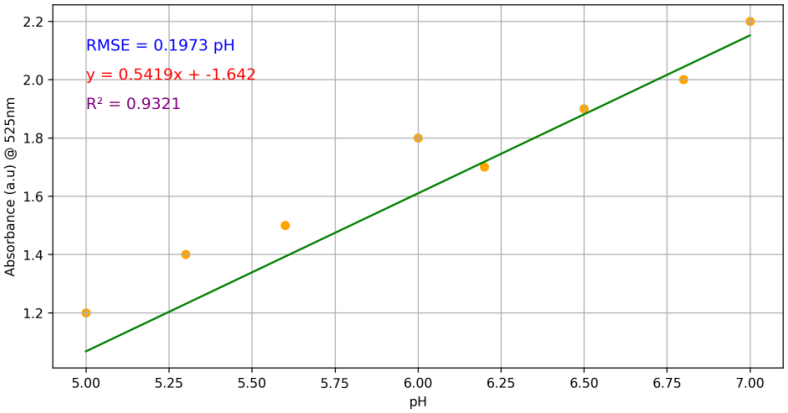

Fig. 3. Response time for CO_2 detection in phenol red.

4 Conclusion

Employing the portable device enables swifter identification of incorrect intubation and facilitates earlier reintubation. A non-invasive colourimetric detector, designed for bi- omedical applications, measures CO2 levels in exhaled breath. Utilising a highly selec- tive dye system, our approach addresses pH effects, response time, reusability, concen- tration impact, and temperature effects in determining CO2 levels. Our findings affirm that colourimetric end-tidal CO2 (ETCO2) monitoring is both safe and reliable by using biocompatible material, minimal invasiveness, no correlation with humidity and repet- itive testing, offering early confirmation of tracheal intubation and prompt detection of oesophageal intubation. Compared to chest auscultation, colourimetric ETCO2 moni- toring confirms endotracheal tube placement more rapidly in both oesophagal and tra- cheal intubations.

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