

Poster: Towards Hardware and Software Integration of Noninvasive Transcutaneous Oxygen Monitor

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ABSTRACT

This paper discusses the crucial features of integrating hardware and software elements of a noninvasive transcutaneous oxygen monitor for personalized medicine. First, we articulate the operating principle of luminescent-based oxygen sensing technique and various hardware prototypes. Then, we present a finite element model investigating the relationship between transcutaneous and arterial oxygen, followed by a discussion about challenges of hardware-software co-design.

KEYWORDS

Biosensors, Machine Learning, Human Circulatory System, Markov Model, Precision Medicine

1 INTRODUCTION

Respiratory parameters are critical indicators of humans' physiological status. However, despite the massive shift towards the use of wearable medical devices, there has been little progress in developing algorithms for personalized precision medicine used in miniaturized respiration devices.

We propose a smart and connected health solution enabling cost-effective remote monitoring of patients with respiratory distress via a miniaturized oxygen monitor with sufficient resolution. Our solution is based on a hardware-software integration framework where luminescence-based oxygen sensors measuring partial pressure of transcutaneous oxygen ($P_{tc}O_2$) are incorporated with computational models of oxygen transport that will accurately translate to partial pressure of arterial oxygen ($P_{a}O_2$). These models will be used to iteratively design an estimation algorithm for the sensor resilient to noise arising from environmental factors, sensor hardware, and intra- and interpersonal variations. Especially capturing interpersonal variations paves the way for personalized respiratory monitoring that enables precision medicine.

The overall system provides massive respiratory data collection outside the medical setting, which has not been available before. With this new data, new biomedical research opportunities will be available to assess therapies and further investigate medical conditions in which oxygen plays a critical role.

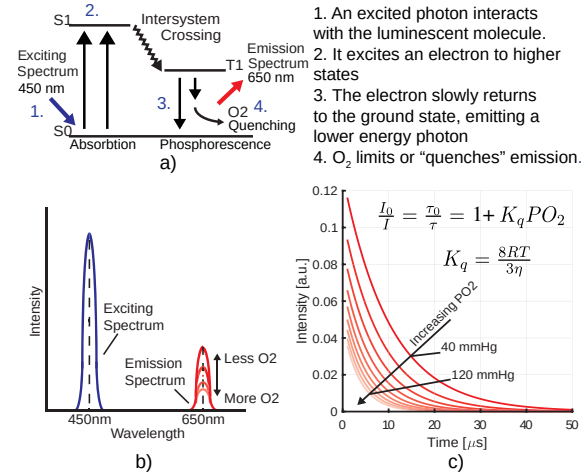


Figure 1: (a) Simplified state diagram, (b) wavelength shift, (c) τ and intensity of the emission quenched by O_2 [1].

2 LUMINESCENT-BASED OXYGEN MONITORS

2.1 Operating Principle

Despite the technology being explored since the 1980s, luminescent-based oxygen (O_2) probes fell out of the medical-radar due to the increased popularity and success of pulse oximetry [2]. However, due to the limitations of the pulse oximetry technique [3] and recent advancements in sensor technology, luminescent technique has re-emerged as an attractive alternate technique to measure noninvasive transcutaneous blood gases [4, 5, 6, 7, 8]. Fig. 1 depicts the concept of luminescent O_2 sensing mechanism. The kinematics of quenching mechanism is described by the Stern-Volmer equation as seen in Fig. 1c. The intensity and lifetime in the presence of oxygen (I and τ) and in the absence of oxygen (I_0 and τ_0) are related to the partial pressure of oxygen (PO_2) in the environment through the rate constant i.e. K_q . Based on results from [9, 10], PO_2 can be accurately estimated by analyzing the time constant of the exponential decay (τ).

2.2 Hardware Implementation

Over the past few years, multiple different hardware prototypes measuring transcutaneous oxygen have been presented, such as an implantable deep tissue oxygen monitor [5], a minimally invasive oxygen monitor [11], and a noninvasive integrated read-out of transcutaneous oxygen [6]. Costanzo et al. presents in [7] a hardware implementation of the luminescent oxygen sensing

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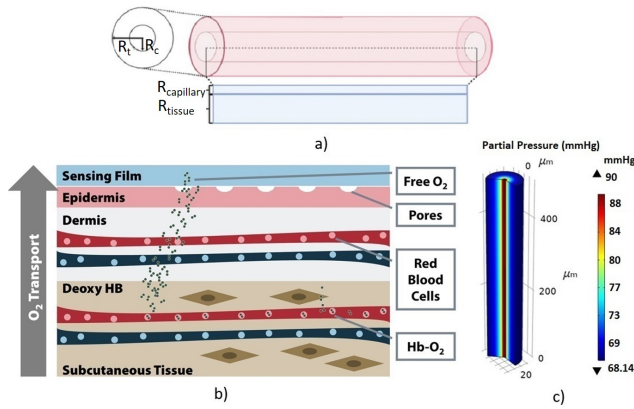


Figure 2: (a) COMSOL simulation geometries. (b) O_2 diffusion through skin layers. (c) O_2 distribution results found by FEM simulations.

technique using a Pt-porphyrin film. The prototype was characterized in bench-top gas testing and analyzed/verified in an small ex-vivo experiment. The bench-top gas testing compared and analyzed the intensity vs. lifetime measurement technique, measuring PO_2 from 0 - 418 mmHg. The lifetime-based measurement clearly showed adequate accuracy across different LED drive currents as compared to intensity-based measurement. The human subject measurement demonstrated that the prototype can detect arterial and venous occlusion events. While the prototype does require improvement in order to accurately resolve variations in the magnitude of nanoseconds, the sensor could accurately resolve the variation in the intensity-based measurement.

3 OXYGEN TRANSPORT MODELING

3.1 Methods

To determine the feasibility of our approach, we used finite element modeling (FEM) along with transport equations for oxygen partial pressures, inside the tissues and capillaries, in a 3D multilayered skin model as illustrated in Fig. 2b, combined with a sensing film layer representing the sensor. The oxygen transport from a single capillary to the surrounding tissue was described based on many models inspired by the seminal work of Krogh's model [12] for oxygen diffusion through tissues. We used COMSOL Multiphysics software to simulate oxygen diffusion through an infinitely long Krogh's cylinder using a rectangular cross-sectional area along with a 2D axisymmetric model as illustrated in Fig. 2a.

3.2 Results

The results of FEM analysis, shown in Fig. 2c, illustrate the O_2 partial pressure distribution from the capillaries to the surrounding tissue assuming a fixed O_2 partial pressure inside the capillary (90 mmHg). We can observe that rectangular 2D axisymmetric model provides a rough approximation of an O_2 partial pressure of 68.14 mmHg at the skin. This model can be extended by stacking the cylinders as building blocks of the tissue with multiple capillaries. Future work entails implementing the different properties of the skin and their effect in oxygen transport such as temperature, humidity, histology, metabolic oxygen consumption, and permeability, along with how each of these parameters varies between individuals based on age, gender, exercise, and other factors.

4 DISCUSSION

The computational models described in Section 3 will be developed with the help of the data collected by the sensor prototypes described in Section 2. This process will enable hardware-software integration where computational models guide the hardware design to reduce noise power requirements, to improve sensitivity, and to construct an estimation algorithm to be embedded in the system to compensate for environmental factors, intra- and interpersonal variations. Challenges towards this integration are i) collecting enough data to support the modeling efforts, ii) developing an algorithm light enough to be run on a wearable, and iii) adjusting power requirements to provide enough power for sensing and computing.

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