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Estimating arterial CO_2 partial pressure by sensor fusion of end-tidal and transcutaneous CO_2 measurements

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Abstract: Closed-loop control of arterial CO_2 partial pressure ($PaCO_2$) could improve respiratory care in preterm neonates but requires an accurate, continuous, and noninvasive surrogate of $PaCO_2$. We propose obtaining such a surrogate by fusing end-tidal and transcutaneous CO_2 measurements. We evaluate two fusion approaches: (i) a linear combination of the two signals and (ii) a state-augmented Kalman filter. Both methods are assessed using mechanical ventilation data from five preterm lambs. In this dataset, both fusion approaches improve $PaCO_2$ estimation compared with either end-tidal or transcutaneous CO_2 alone, supporting their potential use in future closed-loop ventilation systems.

I. Introduction

Monitoring the arterial partial pressure of carbon dioxide ($PaCO_2$) is crucial to ensure adequacy of ventilation settings in mechanically ventilated patients. In preterm neonates, this is of special interest because extremes and fluctuations of $PaCO_2$ are associated with cerebral complications [1].

The Arterial Blood Gas Analysis (ABG), a chemical analysis of an arterial blood sample, is considered the gold standard to determine $PaCO_2$. However, ABGs can only provide intermittent measurements, may cause pain to the patient, and pose risk of infection. Today, two noninvasive and continuous surrogates of $PaCO_2$ are available: the end-tidal partial pressure of carbon dioxide ($PetCO_2$) and the transcutaneous partial pressure of carbon dioxide ($TcpCO_2$). $PetCO_2$ is measured in the breathing gas at the end of exhalation and allows low-delay breath-wise monitoring. It is widely accepted in anesthetized patients but of limited reliability in preterm neonates given their physiological characteristics [2]. Measuring $TcpCO_2$ is based on carbon dioxide diffusion through the skin and requires placement of a heated, adhesive sensor on the skin. $TcpCO_2$ is used more frequently in neonates [2] but requires regular relocation of the sensor to avoid skin damage, leading to frequent sensor downtimes and recalibration requirements.

Beyond informing respiratory care, estimating $PaCO_2$ could enable closed-loop control of $PaCO_2$ in neonates. We have successfully demonstrated the functioning of such a system in preterm lambs using $PetCO_2$ corrected by frequent ABGs as feedback signal, pointing out that providing an accurate, continuous and noninvasive surrogate of $PaCO_2$ remains the biggest challenge for bedside application [4,5]. Fusing $PetCO_2$ and $TcpCO_2$ to estimate $PaCO_2$ could alleviate the challenges associated with each measurement and improve estimation accuracy to enable a closed-loop control system of $PaCO_2$ as shown in Figure 1. Although previous studies have compared $PetCO_2$ and $TcpCO_2$ [2], to the best of our knowledge they have not been combined for $PaCO_2$ estimation. In this work, we present two methods to fuse $PetCO_2$ and $TcpCO_2$ into a single estimate of $PaCO_2$. We use data of five preterm lambs to evaluate the fusion approaches and compare them to estimates resulting from the individual measurements using $PaCO_2$ determined by ABGs as the reference.

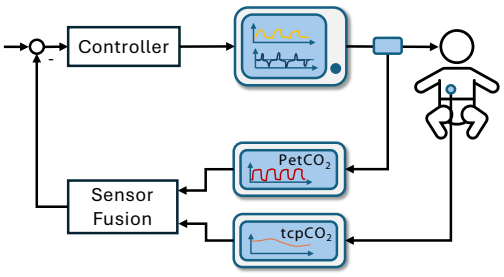

Figure 1: Schematic of the automated mechanical ventilation setup for neonates we envision based on the sensor fusion approach presented in this work.

II. Material and methods

II.I Data

We use secondary data of a study evaluating a closed-loop control system for mechanical ventilation in preterm lambs [3,4,5]. $PetCO_2$ served as base for feedback control and was calculated from the fraction of CO_2 measured in the breathing gas with a proximal CO_2 sensor (Masimo

IRMA, Masimo Corporation, Irvine, USA) [3,4,5]. ABGs were taken regularly every 30 minutes. $TcpCO_2$ was additionally taken in a subgroup of animals using a transcutaneous monitoring device (SenTec Digital Monitoring System, Sentec, Therwil, CH) and had no influence on the closed-loop controller. For this work, the $TcpCO_2$ measurements of five animals were synchronized retrospectively with $PetCO_2$ and $PaCO_2$ using video recordings of the corresponding experiments.

II.I $PaCO_2$ estimation methods

As a first simple approach to fusing $PetCO_2$ and $TcpCO_2$ we propose combining them linearly

$$\widehat{PaCO}_2(t) = w_{et}(PetCO_2(t) + b_{et}) + w_{tc}\,(TcpCO_2(t) + b_{tc}), \quad (1)$$

where w_{et} and w_{tc} are constant weights given to each measurement and b_{et} and b_{tc} are constant biases. We choose to give both sensors equal importance, therefore $w_{et} = w_{tc} = 0.5$, and set the biases to values reported in literature, with b_{et} = 4.1 mmHg and b_{tc} = -0.8 mmHg [2].

Our second approach uses a Kalman filter. To account for inter- and intra-patient variability of the biases, we augment the system state with the measurement biases to estimate them along with $PaCO_2$. In addition, we choose a simple random walk transition model because we expect high model uncertainty. An introduction into state-augmented Kalman filtering can be found in [6].

Finally, we compare the estimates from both fusion methods with those obtained from the two individual measurements, corrected using the same biases as in (1):

$$\widehat{PaCO}_2(t) = PetCO_2(t) + b_{et}, \quad (2)$$

$$\widehat{PaCO}_2(t) = TcpCO_2(t) + b_{tc}. \quad (3)$$

III. Results and discussion

We analyzed 55 hours of ventilation data from five preterm lambs and compared the estimates of the four methods described above to $PaCO_2$ determined by ABGs. The mean difference between $PetCO_2$ and $PaCO_2$ was 3.9 mmHg and the mean difference between $TcpCO_2$ and $PaCO_2$ was 1.1 mmHg. The mean absolute errors (MAE) between the estimates and $PaCO_2$ are shown in Table 1. Both fusion methods increased the estimation accuracy compared to using bias-corrected single measurements with the Kalman filter yielding the lowest MAE. More detailed results are given by the boxplots in Figure 2. The linear combination approach resulted in slightly narrower quartiles, whereas the Kalman filter approach more effectively prevented outliers. Bias-corrected $PetCO_2$ achieved accuracy comparable to that of the fusion approaches, likely because the literature-derived value of b_{et} matched our data closely.

Table 1: Mean absolute error of estimated $PaCO_2$ versus ABG-determined $PaCO_2$ for each estimation method.

Method	Linear Comb.	Kalman filter	$PetCO_2 + b_{et}$	$TcpCO_2 + b_{tc}$
MAE [mmHg]	3.9	3.2	4.1	5.8

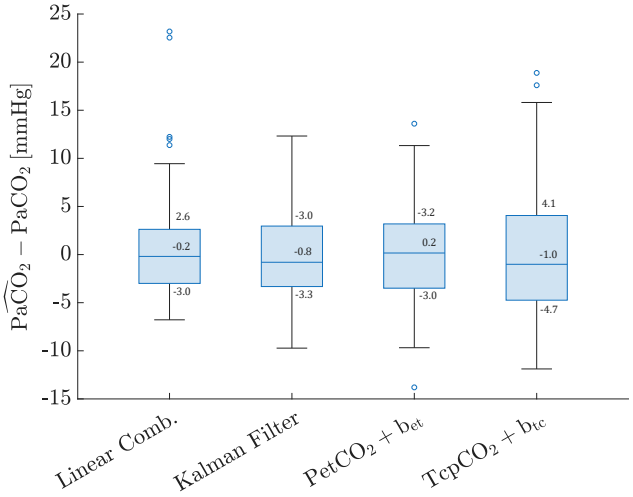

Figure 2: Boxplots of estimation errors for each estimation method with annotated medians and first and third quartiles.

Under conditions with stronger variability of b_{et}, e.g. in lung disease, we expect the benefits of the fused methods to become more pronounced. Beyond improving accuracy, the fused methods provide redundancy, which can be an important safety factor for an automated mechanical ventilation system.

IV. Conclusions

Fusing $PetCO_2$ and $TcpCO_2$ shows promise for improving noninvasive $PaCO_2$ monitoring and for serving as a basis for an automated mechanical ventilation system for preterm neonates. We expect the Kalman filter-based approach to further improve performance by incorporating a more advanced process model and domain knowledge. Further evaluation in a larger cohort and human patients is warranted.

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Author's statement

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