A Prototype towards a Test Bench for Noninvasive Transcutaneous Carbon Dioxide Monitoring Devices

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Lab line of work : health and industry

Physiology study (Medical)

Medical Device Production (Industries)

Technological Innovation for everyone health

Collaborations with Doctors = Human / Innovation link

Collaboration with Industries = Innovation / Techno link

Wereable = System in close proximity to the person
Proof of Concept, first prototype

Meaningful data in response of Doctors needs

Sensor Integration

Data Aquisition

Data Processing

First prototype for future industries production

CEA-Leti Skills

Introduction

- Blood gas monitoring is essential for intense care units.
- The monitoring can be done using several types of medical devices.

Masimo Rad 97TM

Draeger Savina 300

- Interest in developing non invasive devices is growing.
- A possible approach would be to measure transcutaneous gases.

Sentec OxiVenT

- The validation of medical devices require clinical trials that prove to be long and costly.
- An interesting alternative is developing test benches that mimic the physiological parameters that are to be monitored.

Introduction

- This work aims to develop a bench that mimics blood and skin to test a noninvasive transcutaneous CO_2 gas sensor.
- The bench will reproduce similar physiological parameters of the forearm, which is the measurement site of the sensor.
- The gaseous phase will be generated starting from a liquid phase to recreate the same gas diffusion dynamics.
- A novel method for dynamic monitoring of dissolved carbon dioxide ensuring a fast response will be also presented.

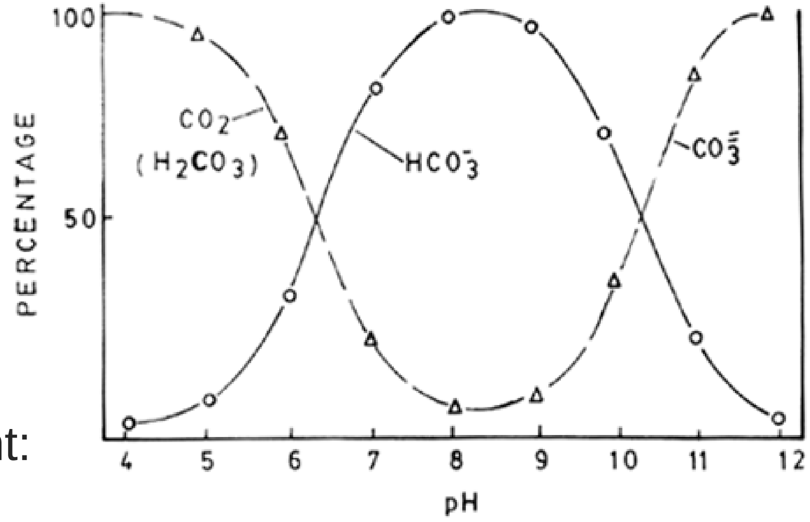
A method to measure dissolved carbon dioxide in a controlled environment

- Carbon dioxide dissolution leads to cascade reactions, the percentage of the resulting ions depends on the pH of the medium:

$$H_2O + CO_{2,aq} \overset{K_0}{\Leftrightarrow} H_2CO_3$$

$$H_2CO_3 \overset{K_1}{\Leftrightarrow} H^+ + HCO_3^-$$

$$HCO_3^- \overset{K_2}{\Leftrightarrow} H^+ + CO_3^{2-}$$



Mole fractions (%) of CO_2, HCO^-_3 and $CO^=_3$ at different pH. (Boyd, 1982)

- These reactions are described by their equilibrium constant:

$$K_1 = \frac{[H^+][HCO_3^-]}{[H_2CO_3]\ C_0} \qquad K_2 = \frac{[H^+][CO_3^{2-}]}{[HCO_3^-]\ C_0}$$

- The conductivity of the system :

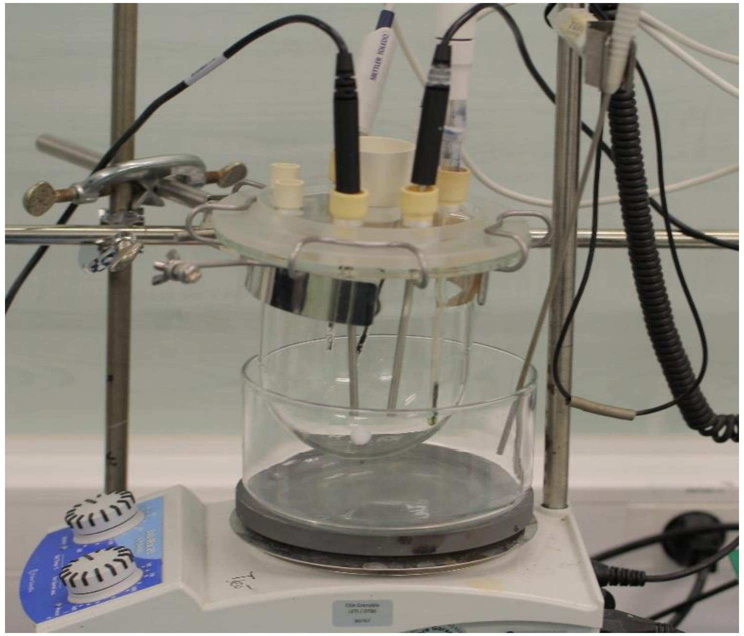
$$\sigma = \lambda_{HCO_3^-}[HCO_3^-] + 2\lambda_{CO_3^{2-}}[CO_3^{2-}] + \lambda_{H^+}[H^+] + \lambda_{OH^-}[OH^-] + \lambda_{Na^+}[Na^+] + \lambda_{Cl^-}[Cl^-]$$

A METHOD TO MEASURE DISSOLVED CARBON DIOXIDE IN A CONTROLLED ENVIRONMENT

- Combining the previous equations allow to compute carbon dioxide concentration :

$$[CO_{2,aq}] = \frac{\sigma - \lambda_{H^+}[H^+] - \lambda_{OH^-}\frac{K_w}{[H^+]} - \lambda_{Na^+}[Na^+] - \lambda_{Cl^-}[Cl^-]}{\frac{\lambda_{HCO_3^-} K_1}{[H^+]} + \frac{2\,\lambda_{CO_3^{2-}} K_1 K_2}{[H^+]^2}}$$

- The input parameters that need to be measured are the :
  - pH,
  - the conductivity,
  - the temperature.
- The several sensors are connected to an acquisition system, plugged to a computer for continuous monitoring.

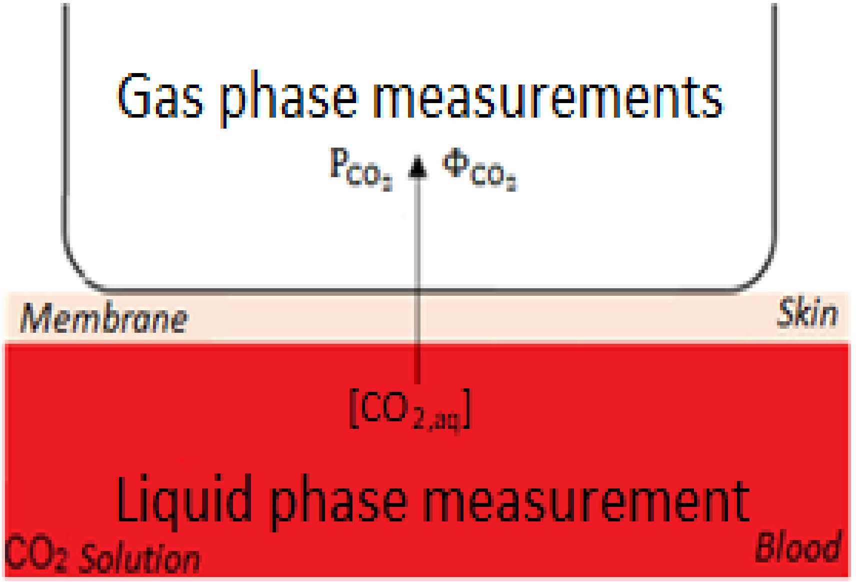


Experimental setup for CO2 monitoring

Test bench conception

- The aim is to mimic the same features as the measurement site that are the partial pressure P_{CO_2} and flux Φ_{CO_2}.
- Carbon dioxide will be generated from a liquid phase to recreate the same diffusion dynamics as in blood.
- The thermodynamic equilibrium between a gaseous phase and the aqueous phase is described by Henry's law :

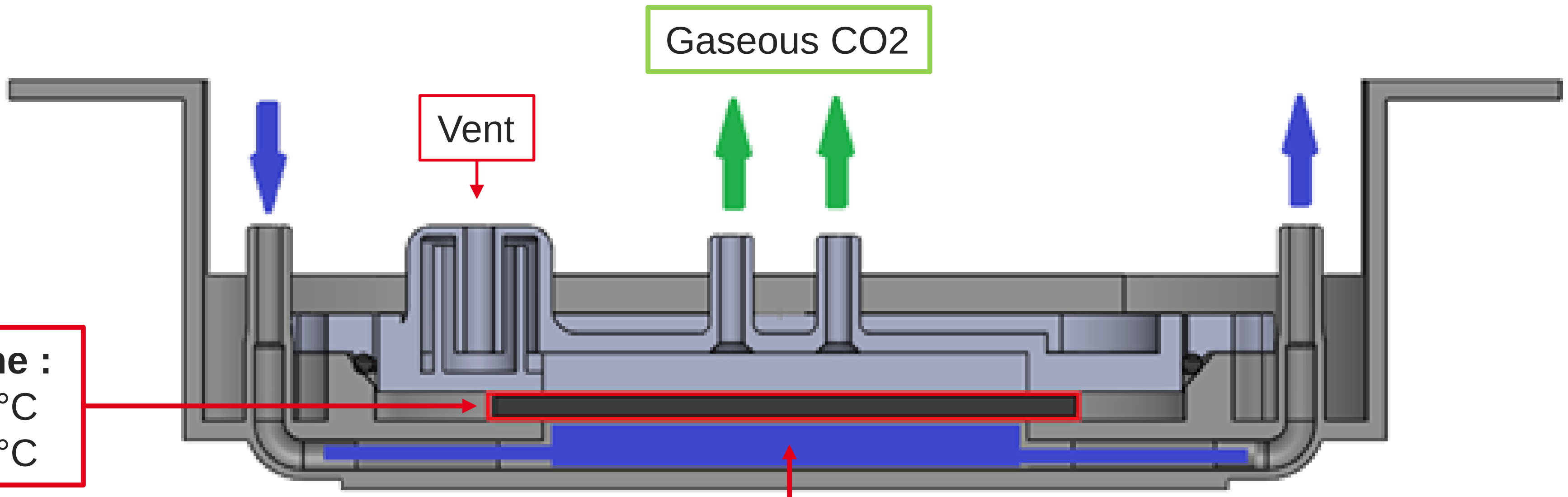
$$[CO_{2,aq}] = \alpha \, P_{CO_2}.$$



- The physiological parameters:

Temperature (°C)	P_{CO_2} (mmHg) [1]	Equivalent $[CO_{2,aq}]$ $(\mathrm{mmol\ L^{-1}})$ at 42°C	Φ_{CO_2} $(10^{-7}\mathrm{mol\ m^{-2}\ s^{-1}})$ [2]
37 – 42	20 - 100	0.6 – 3	7.54

Test bench conception



PDMS membrane :

- 4.3mm at 37°C
- 2.8mm at 42°C

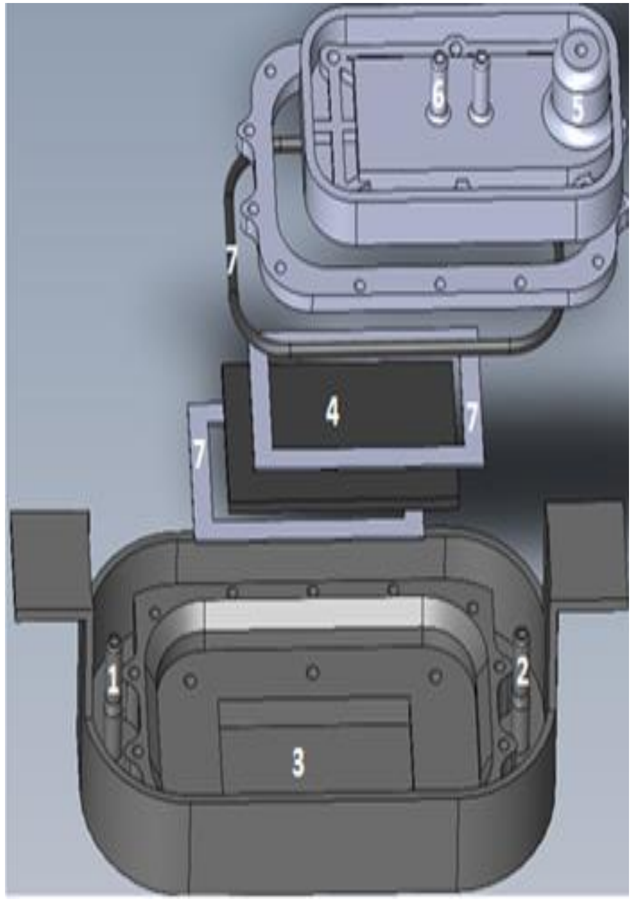
CO2 Solution :

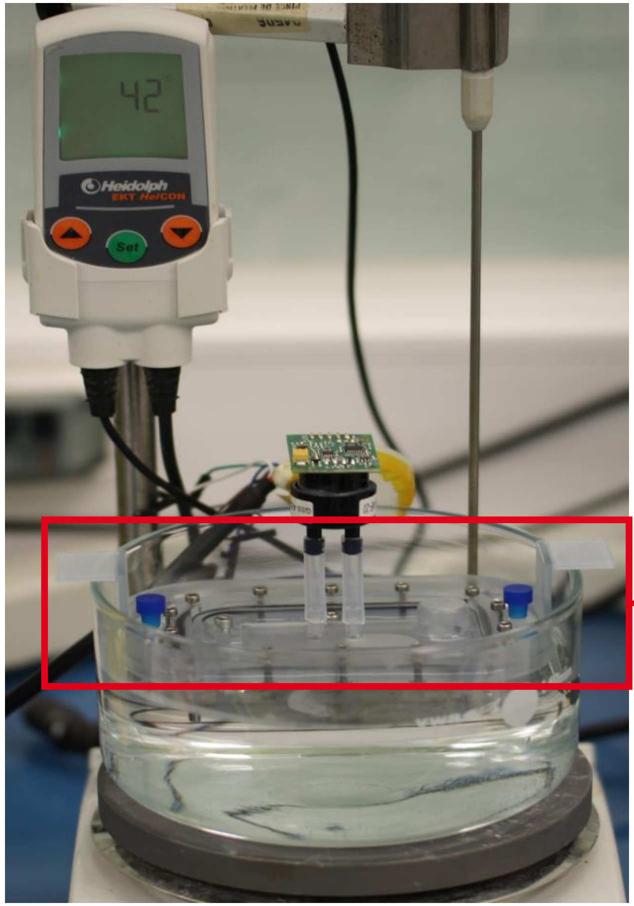
- Standard Hanna HI 4005-01 at 0.1 $\mathrm{mol\,L^{-1}}$
- Reagecon SC026C at 6 $\mathrm{g\,L^{-1}}$
- Otec sodium chloride 0.9% sterile pyrogen-free solution

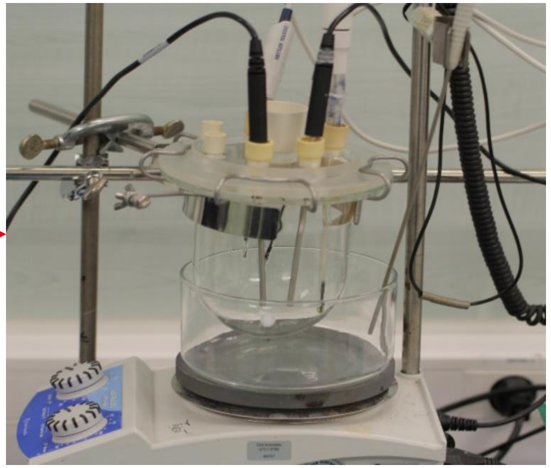
Section view of the test bench

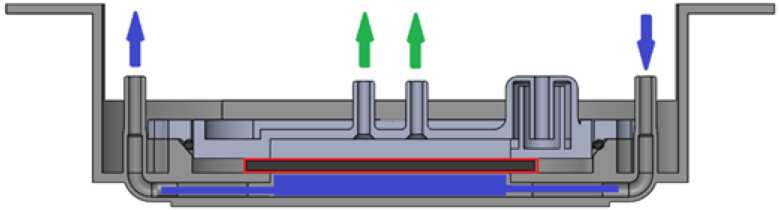
Test bench conception

- The $[CO_{2,aq}]$ in the liquid phase is monitored using the previously presented method.
- The P_{CO_2} in the gaseous phase is monitored using a SprintIR-WP20 gas sensor.



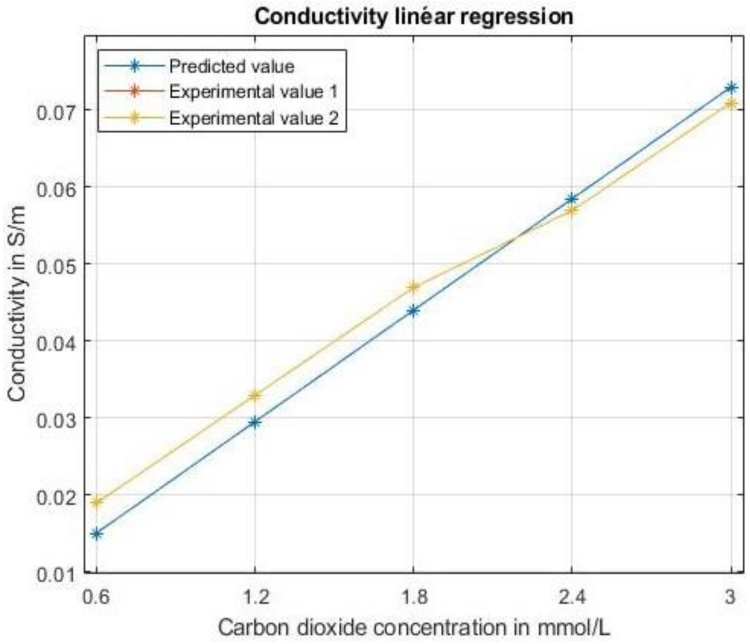


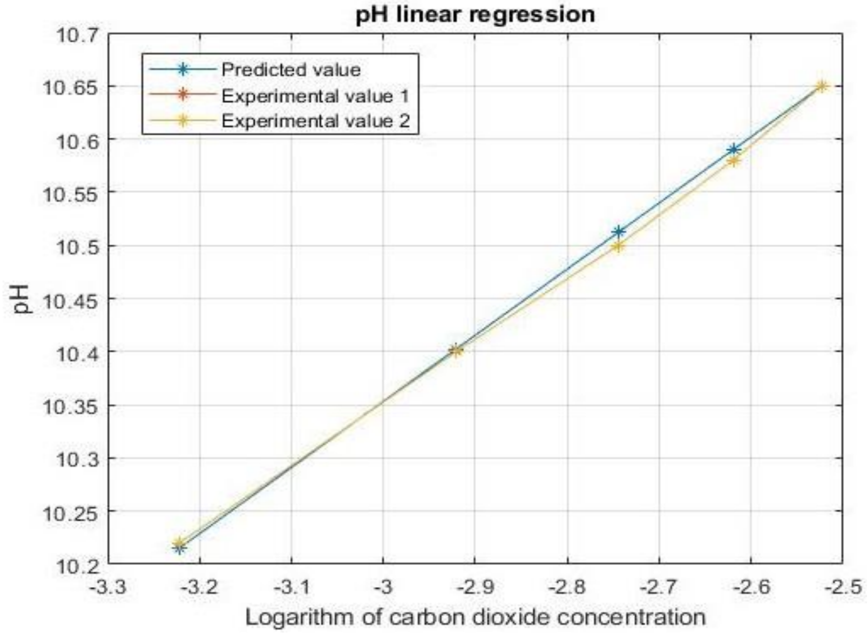




Results

- The proposed method to monitor $[CO_{2,aq}]$ validates the linear relationship between:
  - $[CO_{2,aq}]$ and the conductivity,
  - $[CO_{2,aq}]$ logarithm and the pH.





- Three values of each five-fold measurement point were randomly chosen to create a linear regression learning batch.

Conclusion

- The presented results validate the proposed method for dissolved carbon dioxide monitoring.
- The approach is also valid in the dynamic regime with a few seconds response time.
- The final goal is to be able to control the partial pressure P_{CO_2} above the membrane by adjusting the concentration $[CO_{2,aq}]$ in the liquid phase while matching the transcutaneous flux Φ_{CO_2}.
- A similar test bench will be developed for dioxygen, both benches will be used to develop a non invasive device for transcutaneous blood gas monitoring.

Thank you for your attention

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References

[1] X. Bobbia *et al.*, “Concordance and limits between transcutaneous and arterial carbon dioxide pressure in emergency department patients with acute respiratory failure: a single-center prospective observational study,” *Scand J Trauma Resusc Emerg Med*, vol. 23, no. 1, p. 40, Dec. 2015, doi: 10.1186/s13049-015-0120-4

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