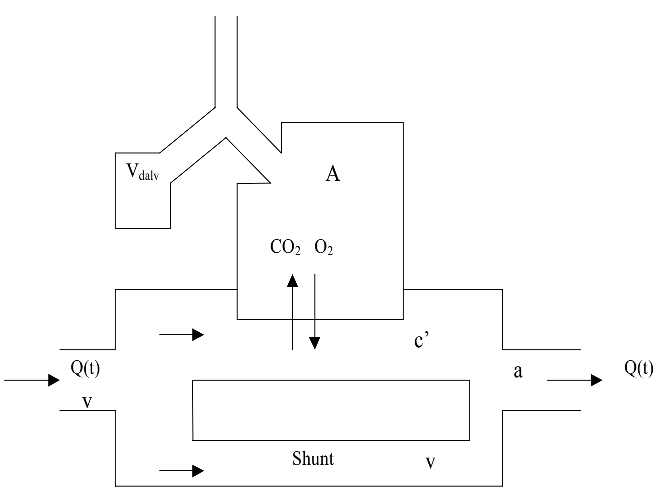
GAS EXCHANGE MODELING FOR PREDICTING PULMONARY AIR EMBOLISM AND EDEMA IN REAL TIME

Rachana Visaria* and Dwayne Westenskow*+
*Department of Bioengineering,
+Department of Anesthesiology,
University of Utah, Salt Lake City, Utah, USA

Abstract

A four compartmental gas exchange model for predicting pulmonary air embolism and edema in real time on a mechanically ventilated patient was developed. The technique is fully automated, requires minimum input parameters and makes few assumptions. The model was based on Fick's principle, shunt equations and well accepted, standard empirical equations obtained from the literature. The required input variables are – Inspired and Expired O_2 and CO_2, SaO_2 and air flow rate measured at the mouth. The assumptions made were - end-capillary pressures of O_2 and CO_2 were same as the alveolar partial pressure of O_2 and CO_2, respectively. Also, the shunted blood has same O_2 and CO_2 concentrations as the mixed venous blood. An exhaustive search routine was applied to determine alveolar and arterial O_2 and CO_2 partial pressures. The shunt, physiological dead space and hence the V/Q mismatching can then be calculated from these variables. The embolism is known to increase physiological dead space (Vdead) and edema is known to increase physiological shunt (fs). But it was observed that both Vdead and fs change in embolism and edema. However, Vdead/Tidal volume normalized with paCO2 increases in case of embolism and decreases in case of edema. Also, RQ decreases in embolism and increases in edema. The effects of increasing dose of air emboli on various respiratory parameters were also studied.

Model



Assumptions

$$P_{c'O_2} = P_{AO_2}$$
$$P_{c'CO_2} = P_{ACO_2}$$

Input parameters:

- Inspired and expired O2 and CO2
- SaO2
- Air flow rate at the mouth

Output parameters
- Arterial and alveolar gases
- Shunt, dead space, V/Q, RQ

$$\dot{Q}_{(t)} \times (1 - fs) = \frac{\dot{V}_{CO_2}}{(C_{vCO_2} - C_{c'CO_2})}$$

$$\dot{Q}_{(t)} \times (1 - fs) = \frac{\dot{V}_{O2}}{(C_{c'O_2} - C_{vO_2})}$$

Model Analysis

Using Fick's Principle,

$$(1 - fs) \times C_{c'CO_2} + fs \times C_{vCO_2} = C_{aCO_2}$$

$$(1 - fs) \times C_{c'O_2} + fs \times C_{vO_2} = C_{aO_2}$$

Using basic shunt equations,

$$C_{CO_2} = (6.957 * [Hb] + 94.864) \times \ln(1 + 0.1933 \times P_{CO_2})$$
$$C_{O_2} = (P_{O_2} \times \alpha) + (S_{O_2} \times Hb_{capacity} \times Hb_{conc})$$

From Capek and Roy [1]

$$\log pO2 = 0.371 \log(\frac{S}{1-S}) - 0.48(pH - 7.0) + 0.019T + 0.92$$

From Rossing and Cain [2]

Using the above equations and exhaustive search procedures, the arterial and alveolar gases and hence the dead space and shunt were calculated.

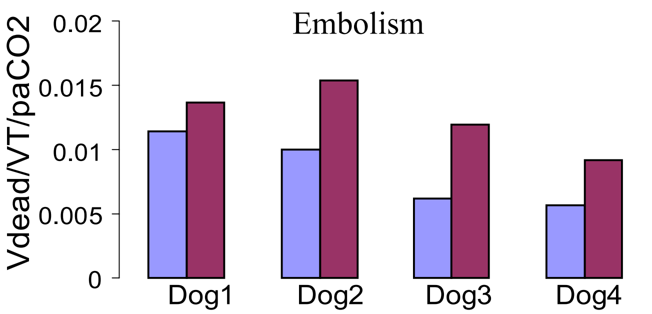
Methods

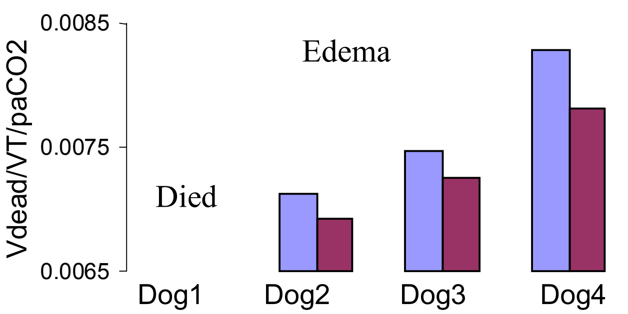
Four dogs were deeply sedated with 1.5 ml of Telazol given as an IM injection. When the animal was recumbent its trachea was intubated with an endotracheal tube and mechanically ventilated with Forane (1% -3%) in oxygen to maintain pCO_2 at about 40 mmHg. An IV was started in the cephalic vein and was given at a rate of about 10 ml/kg/hr. End tidal gases (CO_2, Forane and O_2) were continuously monitored. Inspired respiratory gases (O_2 and CO_2) were monitored.

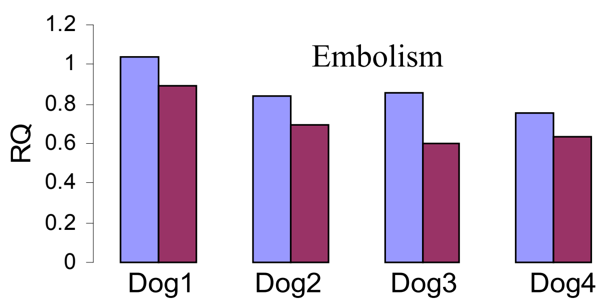
Pulmonary Embolism: A serial IV injections of air (1, 1.5 and 2 ml/kg) was performed over 2 sec. The air was injected in superior vena cava. Acute pulmonary embolism lasted for about 10-20 min. Hence injections were given in 30-min intervals.

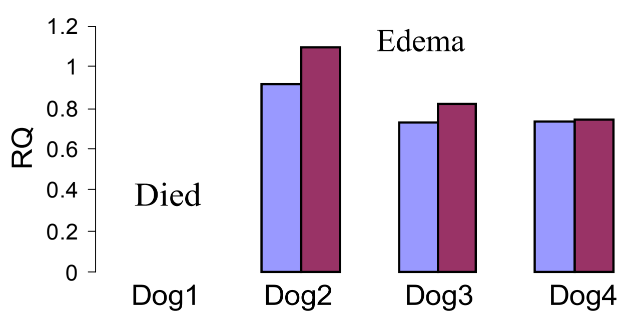
Pulmonary Edema: An iv dose of 0.2 ml/kg of Oleic acid was injected in superior vena cava of each animal via the pulmonary arterial catheter.

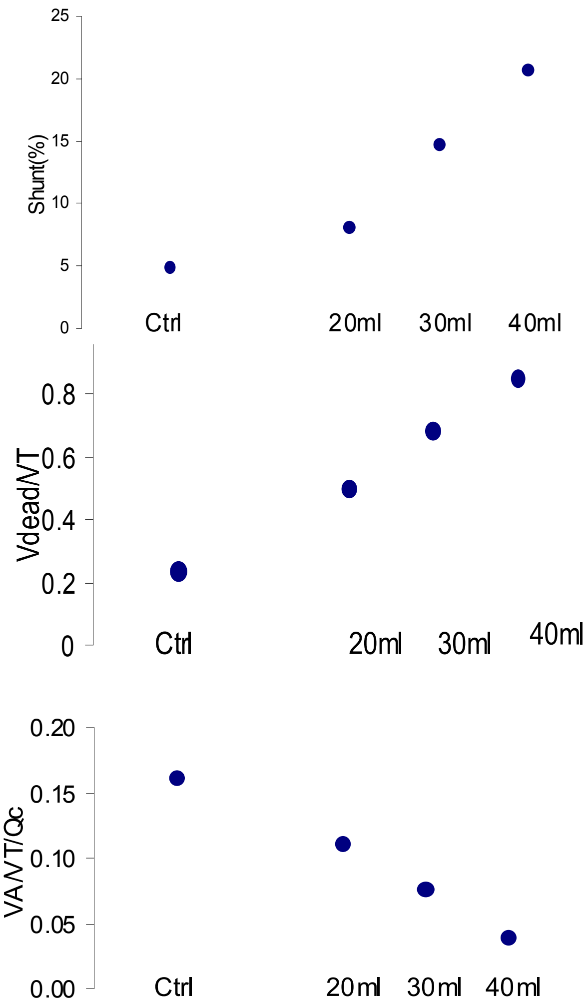
Results











Effects of increasing air emboli dose

Conclusion

A new method has been developed that can predict dead space and shunt noninvasively with minimum physiological monitoring. RQ and Vdead/VT/paCO2 have been identified as potential parameters to diagnose and separate embolism from edema. Vdead/VT and ventilation/perfusion fail to separate embolism from edema. The changes in shunt and dead space are linear with increasing embolism dose.

References

1) Capek, JM and Roy, RJ, "Noninvasive measurement of cardiac output using partial CO2 rebreathing" IEEE Trans on Biomed Engg; 1988; 35(9); p 653-661.
2) Rossing, RG and Cain, SM, "A nomogram relating PO2, pH, temperature and hemoglobin saturation in the dog" J Appl Physiol; 1966; 21(1); p 195-201.