SimBioSys Pulmonary Mechanics and Peripheral Oxygen Transport (E7 and E8)

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E7 – Respiratory Mechanics

In this exercise, you will investigate lung statics and dynamics using a mechanical ventilator. The mechanical ventilator is pump that forcibly inflates the lungs, optionally holds the lungs at a fixed volume, and then lets the lungs deflate on their own. Most ventilators have an additional feature; they can shut off the lung's deflation when the airway pressure falls below a preset level. This level is termed the positive end-expiratory pressure (PEEP). This is one of the standard settings on the SimBioSys ventilator and one that you must understand in order to understand lung mechanics. For this exercise, we will ignore gas exchange and focus attention on respiratory mechanics.

Terminology

- **VL** Lung Volume, the instantaneous volume of the lungs as they inflate and deflate, which ordinarily varies between 2 and 7 liters.
- **Pao** Airway Pressure is the instantaneous pressure measured at the airway opening (the mouth or the endotracheal tube). This varies between 0 and 20 cm H2O in ventilated patients with normal lungs.
- **Palv** Alveolar pressure is the instantaneous pressure in the alveoli. Typically, this is 0 to 20 cm H2O in ventilated patients with normal lungs.
- **PEEP** Positive End Expiratory Pressure is the applied airway pressure at the end of expiration. This is a ventilator setting, not a property of the lung.
- **Ppl** Pleural Pressure is the instantaneous pressure in the pleural space (between the lungs and the chest wall). Pleural pressure is about - 5 cm H2O (that is below atmospheric) at the end of expiration.
- **Raw** The resistance in the airways - the pressure drop between the airway opening and the alveoli, divided by the flow rate. This reflects how congested the airways have become.
- **SGaw** Specific (S) Airway (aw) Conductance (G). Airway conductance is the reciprocal of airway resistance, and is approximately proportional to lung volume. Specific airway conductance is normalized to lung volume, and so is a better parameter for characterizing the resistive aspect of lung pressure flow dynamics.
- **TLC** Total Lung Capacity is the volume the lung assumes after a maximal inflation effort, usually about 7-8 liters.
- **FRC** Functional Residual Capacity is the volume remaining in the lung after a normal passive expiration, at a zero airway pressure. It is usually about 3 liters.
- **VL,ee** End Expiratory Lung Volume is the instantaneous lung volume at the end of a dynamic expiration; it will be greater than FRC if there is applied PEEP or if the next inspiration begins before the last expiration ended.
- **RV** Residual Volume. This is the volume of the lung after a maximal expiratory effort. It is usually about 2 liters.

Pao,ip Inspiratory Pause Pressure. For an inspiratory pause, one holds the lungs at a constant volume at the end of inspiration and measures the airway pressure; this is the equivalent of a breath hold by a mechanical ventilator. The inspiratory pause pressure therefore equals the alveolar pressure at the peak of lung inflation during a standard ventilatory cycle.

Pao,ee Expiratory Pause Pressure. For an expiratory pause, one holds the lungs at constant volume at the end of expiration; the expiratory pause pressure measures the residual airway pressure at the end of a timed expiratory cycle.

TV Tidal Volume is the volume of air inspired during each breath. Usually about 500 ml.

CL Static Lung Compliance. The ratio of tidal volume to the change in pressure that accompanies inflation of the lungs by this volume.

Required Equation(s)

Static Lung Compliance

CL = TV/(Pao,ip - PEEP)

Exercises (E7)

In these exercises, you will adjust settings on a mechanical ventilator, and you will observe effects on lung volume and pressures. If you haven't done so yet, minimize the Clinical Tools Window, load exercise E07.EXR and arrange the viewers. When you load this exercise, you patient's spontaneous respiratory efforts will be shut off, and the patient will be placed on a ventilator.

Determinants of the FRC (Procedure 1)

In a mechanical sense, the respiratory system is a balloon (the lung) inside another balloon (the chest wall). The gas volume of the two are the same, and the pressures are additive. At FRC, the outward recoil of the chest wall precisely balances the inward recoil of the lung.

a. The mechanical ventilator is found in the Clinical Tools window. Examine it; note that it has a number of different display panels, and these are arranged in the same tabbed fashion as the Clinical Tools window itself. On the "Controls" panel, you will get the standard ventilator controls, which include the tidal volume to deliver, the respiratory rate (the number of breaths given each minute) and the PEEP.

   Record peak pressure. Then, step the tidal volume to 1 liter, and then to 1.4 liters, recording the tidal volume and peak pressure with each increment. Calculate an effective compliance as the ratio of tidal volume to peak pressure, for the minimum and maximum tidal volumes. Why does the compliance change? After this exercise, restore the tidal volume to 600 ml and minimize the ventilator.

b. Record FRC, end expiratory lung volume, and end-expiratory pleural pressure. Why is the end-expiratory pleural pressure negative?

c. If the PV curve viewer is an icon at the bottom of the screen, restore it. Note three pressure volume curves: the lung, the chest wall, and the combined respiratory system. Make the lung stiffer by doubling the amount of elastin, and observe the change in the shape of the pressure volume relationship. It will take about 5 seconds to see the curve change. Record the new value of FRC and end expiratory pleural pressure. Why did these values change? What happened to peak pressure? Restore the elastin amount to its normal value. How does the amount of elastin affect lung volumes and the lung PV curve?

e. Using the ventilator, increase the PEEP level to 20 cm H2O in four steps of 5 cm H2O. Wait for mechanical equilibrium at each state (about 30 seconds). At each increment, record the end-expiratory lung volume and the end-expiratory pleural pressure. What is the effect of PEEP on these variables? Why does this occur? Before going on, return the PEEP to zero.

Determinants of Instantaneous Airway Pressure (Procedure Part 2)

The driving force for airflow between alveoli and airway is the pressure difference between the two. This pressure difference is expended driving air across the resistive drop of the airways themselves. For this exercise, minimize the lung and chest wall static curve windows, and observe the lung pressure waveform window. You will need to display the waveforms and the ventilator side-by-side, so read the instructions and then minimize this window.

a. Examine the three pressure waveforms: the alveolar pressure, the pleural pressure and the airway pressure. Superimpose them (click on the viewer to select it, and press the superimpose waveform button on the toolbar). What accounts for the difference between pleural and alveolar pressure?

b. Open the ventilator, increase the inspiratory pause time to 0.5 seconds, and minimize it again. Note the changes in the superimposed pressure tracings. The airway pressure exceeds alveolar pressure during inspiration, and the reverse holds during expiration. What factors contribute to the difference? Why do the two pressures become identical during the inspiratory pause?

c. Increase inspiratory flow rate to 90 liters/second. What happens to the difference between the airway and alveolar pressure? Return the inspiratory flow rate to 30 liters/second.

d. Decrease the lower airway conductance to 0.4. What happens to the difference between airway and alveolar pressure? What happens to the rate of expiration?

Asthma Simulation (Procedure 3)

It is possible to impose an expiratory pause in a mechanical ventilator. This maneuver shuts off expiratory flow, and the pressure in the airway becomes equal to the alveolar pressure. This is an excellent method for determining whether the alveolar pressure has fallen to the PEEP level at the end of passive expiration.

a. Open the ventilator. Set the PEEP at zero. Switch to the options page, and set the inspiratory pause at zero. Record the end-expiratory lung volume, FRC, and peak pressure. Press the expiratory pause button, and wait for the expiratory pause pressure measurement to be displayed; record this value.

b. Now, reduce the specific airway conductance down to 0.05. This is similar to what happens during severe asthma. What happened to peak pressure? What happened to lung volume? Why is end-expiratory lung volume larger than FRC? Repeat the expiratory pause measurement. What happened to the expiratory pause pressure?

c. You have now created a crude facsimile of a patient with severe asthma. The lung is now hyperinflated, the increase in intrathoracic pressure impairs venous return, and the peak pressures are now very high. In order to lower the pulmonary hyperinflation, it is important to maximize the time for exhalation. To accomplish this, increase the inspiratory flow rate to 90 liters per second. Note that the peak pressure becomes much higher. Repeat the expiratory pause maneuver. Why did the expiratory pause pressure decrease?

E8 – Peripheral Oxygen Transport

The goal of this exercise to explore the relationships between blood flow, hemoglobin concentration, oxygen demand, uptake and delivery, arterial oxygenation, and mixed venous oxygen saturation. The mechanical ventilator will be used in this exercise.

Terminology

VO2	The rate of oxygen consumption for the whole body. Normal value 250 ml/min. This is often normalized to body weight; typical values is 3.5 ml O2 per kg body weight per minute.
QO2	The rate of oxygen delivery via blood to the peripheral circulation. This is usually given in ml O2/kg body weight/minute. Normal value approximately 15 ml/kg/min.
Qt	The cardiac output. This is usually given in liters per minute. Note that hemoglobin and oxygen contents are given as ml/dl, necessitating conversion to dl/min for, e.g., calculation of oxygen delivery. Normal value approximately 5 l/min.
CaO2	The oxygen content in arterial blood. This is usually described as the volume at STP, in ml, of all the oxygen that could be recovered from a deciliter of blood. Normal value approximately 20 ml/dl.
SaO2	The fractional oxygen saturation of hemoglobin in arterial blood, usually written as a percentage. Normal value 95% or more.
SvO2	The fractional oxygen saturation of hemoglobin in mixed venous blood, usually written as a percentage. Normal value is about 70%.
FIO2	The fraction of oxygen in the inspired air. Normal value 21%.
[Hb]	The concentration of hemoglobin in blood, usually expressed as grams per deciliter. Normal value 14 g/dl.
ER	Extraction Ratio: the fraction of oxygen extracted by peripheral tissues on a single pass through the peripheral circulation, often expressed as a percentage. Normal value is about 25%.
aO2	Solubility of oxygen in plasma, approximately 0.003 ml/dl/Torr.

Equations

Oxygen carried by blood

$$CaO2 = [Hb]\ SaO2 + PaO2\ aO2$$

Oxygen delivery to tissues

$$QO2 = CaO2\ Qt$$

Oxygen Extraction Ratio

$$ER = VO2\ /QO2$$

Oxygen Delivery-Uptake Relationship (Figure 1)

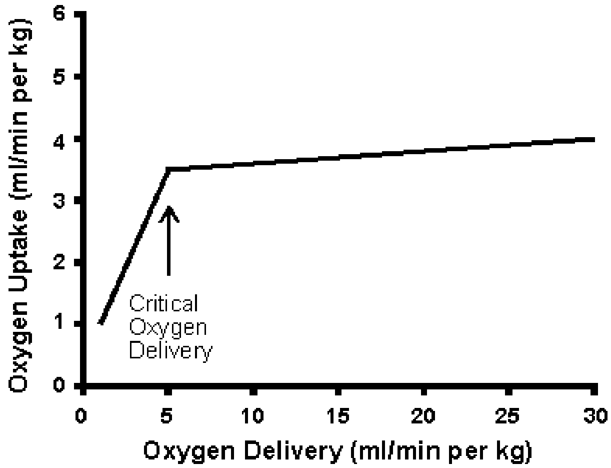

Figure 1: When oxygen uptake is plotted against oxygen delivery, a biphasic relationship is seen. At high levels of delivery, oxygen uptake is set by tissue oxygen demand. By contrast, oxygen uptake falls off when oxygen delivery falls below a critical threshold.

Exercises (E8)

In these exercises, you will adjust settings on a mechanical ventilator, give fluids, withdraw blood, and give drugs. Your goal will be to learn about the relationship between oxygen delivery and uptake, and about the Fick relationship.

If you haven't done so yet, load exercise E08.EXR. When you load this exercise, the patient's cardiovascular reflexes will be disabled, the patient's alveolar ventilation will be set and not subject to change. This is not the normal circumstance, but it will avoid letting interaction of multiple physiological systems confuse your study of the peripheral oxygen transport system.

Procedures

Hypoxic Hypoxia: Reduced FIO2 (Procedure 1)

The simplest and most direct method for reducing oxygen transport is to reduce the oxygen in the inspired air (FIO2). There is no clinical reason to lower the fraction of oxygen in inspired air below it normal value (21%). However, it sometimes occurs in industrial accidents. In this exercise, you will do it in order to learn about responses to hypoxia.

a. Record the SaO2, SvO2, QO2, Qt, CaO2, and ER. These values are all in a normal range. All sympathetic and parasympathetic responses have been interrupted, so that changes in oxygen delivery will have simple effects that are not clouded by autonomic responses. Next, you will reduce the arterial saturation to half its baseline value. Before doing so, write down what you predict will happen to SvO2, QO2, Qt, CaO2, and ER.

b. Using the ventilator tool, decrease the FIO2 until the SaO2 falls to about half of its baseline value. Wait for the blood gases to stabilize, and again record the current values of SaO2, SvO2, QO2, Qt, CaO2, and ER. Did your predictions match the results?

Can you think of a clinically important circumstance that has a physiological effect similar to direct reduction of FIO2?

c. Return FIO2 to 21%, in preparation for the next exercise.

Stagnant Hypoxia: Reduced Qt (Procedure 2)

Cardiac output is a critical determinant of oxygen delivery. The lower the cardiac output, the lower the oxygen delivery will become. A simple way to reduce cardiac output is to reduce venous return by increasing intrathoracic pressure.

a. Record the SaO2, SvO2, QO2, Qt, CaO2, and ER. These values should now be back to normal. In the next step, you will decrease cardiac output by 50%. Write down your predictions for what should happen to each of these variables.

b. Cardiac output is available for direct manipulation in this exercise. Reduce cardiac output by half. You will need to wait a minute or two to gas exchange consequences stabilize. Once again, record the SaO2, SvO2, QO2, Qt, CaO2, and ER. How did each of these variables change -- did it match your predictions?

c. Return Cardiac output to 5.5 liters/min in preparation for the next step.

Anemic Hypoxia: Reduced Hemoglobin (Procedure 3)

Blood hemoglobin concentration is a major determinant of oxygen delivery. The lower the cardiac output, the lower oxygen delivery. In this exercise, you will reduce hemoglobin without changing either arterial oxygen saturation or cardiac output. It is quite a trick to lower hemoglobin without changing cardiac output. Simply removing blood won't work, because the reduction in blood volume will reduce mean systemic pressure, and thus venous return. A better strategy is to perform "isovolumic hemodilution" by removing blood and replacing it, volume for volume, with plasma or some substitute. This strategy is sometimes used clinically as a therapy for acute correction of polycythemia.

a. Record the [Hg], SaO2, SvO2, QO2, Qt, CaO2, and ER. These values should now be back to normal. In the next step, you will decrease blood hemoglobin concentration by 50%. Write down your predictions for what should happen to each of these variables.

b. Perform a 2000 ml phlebotomy at a rate of 10000 ml/hr, and begin it by pressing Start. While it is proceeding, start a 2000 ml FFP (fresh frozen plasma) infusion, at a rate of 10000 ml/hr. Perform this 2 liter exchange transfusion twice, and the hemoglobin concentration is about half of its initial value. Once again, record the [Hg], SaO2, SvO2, QO2, Qt, CaO2, and ER. How did the changes match your predictions?

Supply Dependency (Procedure 4)

For a resting human, a 50% drop in oxygen delivery can ordinarily be compensated by an increase in extraction. Thus, oxygen delivery exceeds the minimum required by more than a factor of two. Provided this minimum is exceeded, oxygen uptake is determined by metabolic O2 demand, and extraction ratio is inversely related to the level of delivery. Continued reductions in delivery will, however, fall below the minimum required threshold -- the critical oxygen delivery (See Figure 1).

a. Unlike prior exercises, begin this one in the anemic state produced as a result of the intervention in the last exercise; do not reset, or reload the case. Record VO2, VCO2, QO2, Qt, CaO2, and ER. Note that delivery and output are reduced compared to normal; VO2 and VCO2 are still at their normal level.

b. Reduce the FIO2 to 11%. Then, set the cardiac output at 4. Wait for the system to stabilize, and again record VO2, VCO2, QO2, Qt, CaO2, and ER. How did each one change? Why did VO2 decrease? Why did VCO2 decrease? If you leave the simulation in this state, you will see blood pH progressively drop. Why would this occur?