RESPIRATORY MONITORING AND OXIMETRY

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Introduction

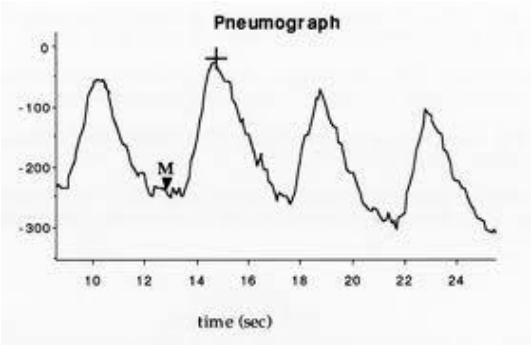
- Respiratory monitoring includes measurement, evaluation, and monitoring of parameters of respiratory system,
- First Group: Parameters of respiratory mechanics and of the mechanics of machine-assisted artificial respiration
  - e.g., Respiration rate, tidal volume, and airway pressure as part of settings at ventilator
- Second Group: Parameters of gas exchange
  - Pulse oximetry
  - Pulse CO-oximetry
  - Transcutaneous blood gas monitoring
  - Capnography

Respiratory Mechanics

- Respiratory mechanics is primarily description of mechanical processes of the thorax necessary for ventilation in form of Pressure/volume relationships
- In the case of patients under artificial respiration, airway pressure and tidal volume are of particular interest
- Variables and behavior of parameters are dependent on compliance (elasticity) of the lungs and on airway resistance

Monitoring of Respiration Rate (RR)

- Vital parameter for such applications as neonatal monitoring
- Impedance pneumography (indirect method)
  - Increase and decrease in thoracic volume linked to inspiration and expiration lead to increase and decrease of impedance of thorax
  - To detect this, very low high-frequency constant current (e.g., 10μA at 40 kHz) is conducted through two thoracic electrodes (ECG electrodes)
  - When current is constant, change in impedance causes synchronous change in voltage drop that are displayed as *Impedance Pneumogram* (or respiration waveform) and used to ascertain respiration rate
  - Signal is highly vulnerable to movement artifacts, as every movement of body influences thoracic impedance
- Capnography (indirect method)



Respiration Rate: Determination

- Running average of breaths counted per minute is displayed
- In some monitors, respiration waveform must only exceed a single adjustable trigger threshold to be classified as valid breath
  - Even small artifacts can, therefore, easily lead to a miscount
- Combination of upper and lower thresholds with adjustable interval in between is better and safer than single trigger threshold
  - Upper and lower thresholds span minimum amplitude that must be exceeded by impedance signal in order to intersect both and hence involves depth of respiratory action in valid breath detection

Respiratory Rate: Apnea Monitoring

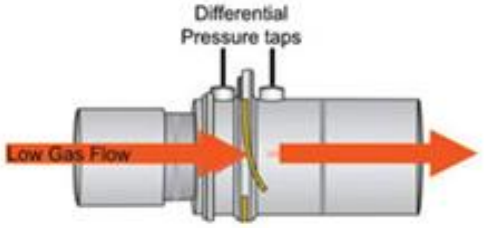
- Counting respiratory actions also makes it possible to monitor any pause in breathing or apnea
- If no breath is detected within time frame defined by adjustable monitoring limit apnea time, then apnea alarm is triggered
- It is important to take into account that every heart beat causes measurable change in impedance in thorax, which may be visible in impedance pneumogram
- If trigger threshold or minimum amplitude is set too low, then it is not respiration rate that is counted but heart rate
  - Cases of apnea can then be overlooked
- In neonatal monitoring mode, monitors are capable of determining whether respiration and heart rates closely resemble one another or are identical and of triggering an alert if this occurs

Pressure and Flow

- In case of artificially ventilated patients, such parameters are set on the mechanical ventilator
  - Not enough to look at set values and actual values must be monitored
- Special flow sensor measures inspiratory and expiratory gas flows and volumes in mainstream and also airway pressure
- Both waveforms of flow, pressure and volume, and also flow-volume (F-V) and pressure-volume (P-V) loops can be displayed on monitor
  - Other parameters that can also be displayed and provided in trends include inspiratory and expiratory tidal volumes, minute volumes, maximum flows and airway resistance, maximum and average airway pressure, PEEP (positive end-expiratory pressure), respiration rate and inspiration/expiration ratio (I/E), and lung compliance
  - If combined with capnography, CO_2 production, alveolar ventilation as well as anatomical and physiological dead space ratios can also be monitored

Flow Sensor with Fixed Orifice

- Important to have robust sensor with small dead space and low flow resistance that can be easily applied to provides reliable measurements without calibration under constantly moist gases
- Special sensor measures gas flows in both directions by measuring differential pressure at flow resistance point in form of fixed orifice
- System is affected less quickly by the negative effects of condensate and can be constructed with such small amount of dead space that it can be used for neonates
- Nonlinear relationship between pressure difference and flow is compensated postprocessing



Different Measurements from Respiratory Mechanics Module and Ventilator

- Ventilators generally measure pressure and volume in equipment remote from patient, whereas the respiratory mechanics module takes measurements close to the patient
- In addition to compliance of ventilation hoses, measuring temperature also plays particularly important role for volumes displayed
- Measurements taken directly from patient are at body temperature (≈ 37 ◦C)
  - These gas conditions are described as BTPS (body temperature and pressure, saturated).
- ATPS (ambient temperature and pressure, saturated) is present in equipment for expiration, and ATPD (ambient temperature and pressure, dry) for inspiration
- Considerable difference in temperature between two measurement points, which leads to noticeable differences in volume

Different Measurements from Respiratory Mechanics Module and Ventilator

- Gas law should be used to compute the changes: $PV = nRT$
- Example: Gas laws give the following equation for an ambient temperature of 22 ◦C:

$$P_{BTPS}\, V_{BTPS} = nRT_{BTPS}$$
$$P_{ATPS}\, V_{ATPS} = nRT_{ATPS}$$

With $P_{BTPS} = P_{ATPS}$, T_{BTPS} = 37 ◦C , T_{ATPS}= 22 ◦C

$$V(\text{BTPS}) = V(\text{ATPS}) \times \frac{273.15 + 37}{273.15 + 22} = 1.05 \times V(\text{ATPS}) .$$

- ATPD condition (standard temperature and pressure, dry) is determined as being at ambient temperature, and pressure that does not include water vapor partial pressure

Gas Exchange Monitoring

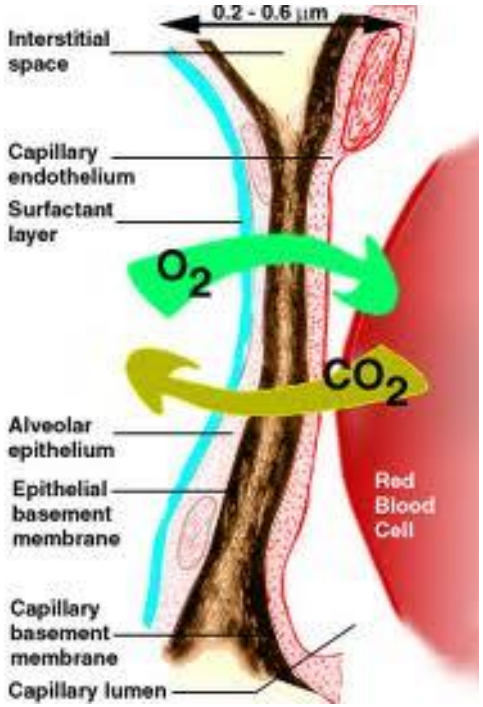
- Measurement methods and measurement parameters for respiratory gases, blood gases, and anesthetic gases can be summarized as so-called gas monitoring under generic term gas exchange
- Differing conditions under which respiratory gases and blood gases of patient must be monitored
  - Spontaneous respiration
  - Artificial respiration with or without oxygen enrichment
- In case of anesthetic ventilation, nitrous oxide N_2O or volatile anaesthetics are added

Gas Exchange Basics

- In pulmonary alveoli, respiratory gases are in contact with blood over short diffusion path via alveolar and capillary walls
- O_2 first dissolves in blood plasma and then diffuses further into red blood cells (RBCs), which contain red blood pigment hemoglobin (Hb) as oxygen-transporting agent
- O_2 is not directly bound to Hb, but is only attached to iron atom of each of four haem groups
  - One molecule of Hb can, therefore, transport up to four oxygen molecules and easily release them again when it reaches surrounding tissue structures having lower oxygen partial pressure via bloodstream
  - Hb is not oxidized, but rather oxygenated and in turn deoxygenated

Gas Exchange Basics

- Carbon dioxide (CO_2) is constantly produced in body as product of metabolism and is likewise partly dissolved in blood plasma, but is for the most part transported back to alveoli as bicarbonate chemically bound by attachment to an NH_2 group of the hemoglobin



Gas Exchange Basics

- Whereas blood gas analysis (BGA) only measures O_2 and CO_2 , concentration of nitrous oxide and volatile anesthetics in respiratory gases must, if necessary, also be monitored
- Respiratory gases are often measured as concentration in percent by volume (vol%), whereas the blood gases are measured as partial pressures in mmHg (= torr) or kPa
  - Both measurements can be converted from one to the other
- In principle it would be physiologically meaningful to present partial pressures under BTPS conditions only but historically inspired gases are given as volume concentration of a dry gas mixture under standard temperature and pressure dry (STPD)

Gas Exchange Basics

- In a mixture of ideal gases with the concentrations c_i measured in vol%), the partial pressure p_i of one component is fraction of total pressure (here always atmospheric pressure p_{baro}) which is proportional to its concentration:

$$p_i = c_i \times p_{\text{baro}}$$

- Total pressure is sum of partial pressures of it gas components:

$$p_1 + p_2 + \ldots + p_n = c_1 \times p_{\text{baro}} + c_2 \times p_{\text{baro}} + \ldots + c_n \times p_{\text{baro}} = p_{\text{baro}}$$

Constituent	Abbreviation	Fraction (vol.%)
Oxygen	O_2	about 21
Nitrogen	N_2	about 78
Argon	Ar	about 1
Carbon dioxide	CO_2	about 0.03

Gas Exchange Basics

- Normal respiratory air with familiar composition is heated to 37 ◦C during inhalation and is mixed with newly added water vapor as result of humidification in the airways
- At full water vapor saturation, water vapor partial pressure p_{H2O} is entirely dependent on the temperature and is 47mmHg at 37 ◦C, which is 6.2 vol% (= (47/760)×100 vol%) at standard atmospheric pressure p_{baro} = 760 mmHg
- With its unchanged composition, respiratory air now takes up only 93.8% of volume
  - In this wet gas, oxygen only has a concentration of 19.7% (= 0.938 × 21%) or a partial pressure of 19.7%×760mmHg = 150 mmHg

Gas Exchange Basics

- Remaining expiration gas in alveoli mixes with this fresh gas, such that a noticeably lower alveolar O_2 partial pressure pAO_2 results, with standard value of ≈ 100mmHg
  - Difference in partial pressures of gas is driving force behind diffusion
- Venous blood arriving in lungs has comparatively low venous oxygen partial pressure pvO_2, which in the capillaries, in ideal ventilation, becomes equal to alveolar partial pressure as result of gas exchange
- Because not all blood is involved in gas exchange, in practice there is alveolar-arterial oxygen difference $AaDO_2$ of 10–20mmHg
- Venous blood transports CO_2 to lungs and inhaled air contains virtually no CO_2 and gas exchange leads to a normal alveolar CO_2 partial pressure *p*ACO2 of ≈ 40mmHg

Gas Exchange Basics

- Spontaneous respiration primarily aims to stabilize CO_2 partial pressure and pH of the blood, whereas large fluctuations in O_2 partial pressure are tolerated
- O_2 is mainly transported by RBCs since Hb binds nearly 70 times more O_2 than plasma
  - One gram of hemoglobin (Hb) can transport ≈ 1.34 ml of oxygen; solubility factor for 1 ml of oxygen in 1 dl of blood is about 0.003 per mmHg
- Amount of oxygen in blood is called the oxygen content (ml O_2 per dl blood)
- How much hemoglobin is loaded with oxygen is dependent on O_2 partial pressure in blood and is given as oxygen saturation
  - Percentage ratio of oxygenated hemoglobin to total amount of hemoglobin

Gas Exchange Basics

- Arterial and venous oxygen content can be given as:

$$caO_2 = 1.34 \times Hb \times \frac{SaO_2}{100} + paO_2 \times 0.003$$

$$cvO_2 = 1.34 \times Hb \times \frac{SvO_2}{100} + pvO_2 \times 0.003$$

- SaO_2 arterial and SvO_2 venous oxygen saturation (%), Hb is hemoglobin content of blood (g/dl), *p*aO2 and *p*vO2 arterial and venous oxygen partial pressures (mmHg)
- Arteriovenous oxygen difference avDO2, unlike AaDO2, is, not partial pressure difference but content difference that provides evidence about O_2 consumption of organism

Gas Exchange Basics

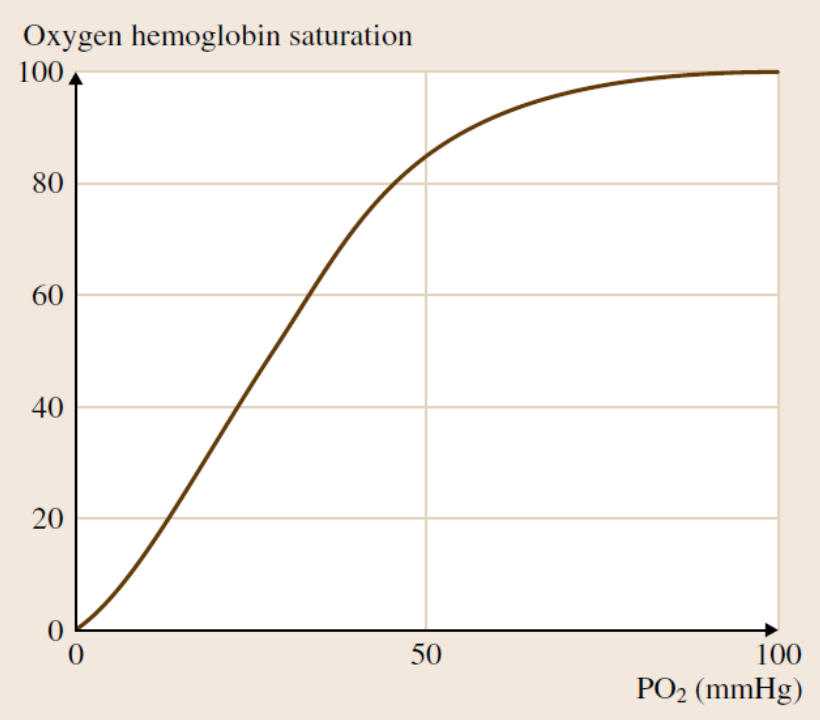
Measurement parameter	Abbreviation	Unit
Hemoglobin content	Hb	g/dl
Oxygen partial pressure		mm Hg or kPa
• Arterial	paO_2	
• Alveolar	pAO_2	
• Venous	pvO_2	
• Transcutaneously measured	$ptcO_2$	
Alveolar-arterial oxygen difference	$AaDO_2 = paO_2 - pAO_2$	mm Hg or kPa
Oxygen saturation		%
• Arterial	SaO_2	
• Mixed venous	SvO_2	
• Central venous	$ScvO_2$	
• Determined by pulse oximetry	SpO_2	
Oxygen content		ml/dl
• Arterial	caO_2	
• Mixed venous	cvO_2	
Arteriovenous oxygen difference	$avDO_2 = caO_2 - cvO_2$	ml/dl
Oxygen availability	$DO_2 = CO \times caO_2 \times 10$	ml/min (CO = cardiac output in l/min)
Oxygen consumption	$VO_2 = CO \times avDO_2 \times 10$	ml/min

Gas Exchange Basics

- In addition to functional hemoglobin Hb (deoxyhemoglobin), available for O_2 uptake, and O_2Hb (oxyhemoglobin), which is already saturated with O_2, there is also a series of dysfunctional Hb derivatives
  - COHb (carboxy-Hb, Hb poisoned with carbon monoxide)
  - MetHb (methemoglobin),
  - Mostly present in the blood in fractions of less than 5 and 1%, respectively
- Whereas amount of O_2 physically dissolved in blood is simply proportional to O_2 partial pressure, significantly more complex relationship between pO_2 and degree of hemoglobin oxygenation (or oxygen saturation) is represented by oxygen–hemoglobin dissociation curve

Gas Exchange Basics

- Position and shape of oxygen–hemoglobin dissociation curve are dependent on various factors in blood, such as:
  - *p*H and *p*CO2
  - Proportion of dysfunctional Hb derivatives (COHb, MetHb)
  - Temperature
  - Hemoglobin type (foetal or adult)
  - Enzyme content (2,3-DPG).



Gas Exchange Basics

- Example 1: With fever or increased pCO_2, dissociation curve is displaced to right, such that oxygen is released to cells more easily
- Example 2: Mountain dwellers have increased 2,3-DPG content, which also results in dissociation curve being displaced to right
- Example 3: Carbon monoxide poisoning with formation of high concentrations of COHb is, in contrast, accompanied by displacement of dissociation curve to the left, such that remaining functional hemoglobin, which is already depleted, also releases the oxygen with greater difficulty

Gas Exchange Basics

- Dangers resulting from decreased supply of oxygen can be detected in good time in arterial blood by monitoring both arterial oxygen partial pressure *p*aO2 and the oxygen saturation SaO2
- Whereas arterial blood samples could previously only be examined for this purpose in laboratory analyzer at relatively long time intervals, noninvasive continuous monitoring procedures are now available for both parameters
  - Pulse oximetry for determining *Sp*O2 as measure of arterial O_2 saturation
  - Transcutaneous blood gas measurement of *ptc*O_2 (and *ptc*CO_2) as correlates of arterial gas partial pressures *p*aO2 (and *p*aCO2)

Gas Exchange Basics

- Hypoxia: low oxygen partial pressure (paO2)
- Hyperoxia: high oxygen partial pressure (paO2)
- Hypoxygenation: low oxygen saturation of hemoglobin (SaO2)
- Hypoxemia: low oxygen content in the blood (caO2)
- Hyperoxemia: high oxygen content in the blood (caO2)
- Anemia: low hemoglobin content in the blood (Hb)

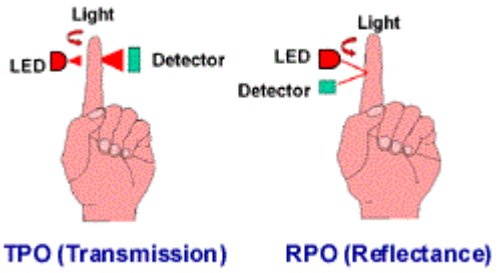
- Similar definitions for CO_2: Hypocapnia, Hypercapnia
  - Hypercapnia normally triggers reflex which increases breathing and access to oxygen, such as arousal and turning head during sleep

Gas Exchange Basics

- It can be seen from oxygen-hemoglobin dissociation curve that, in case of oxygen deficiency, even small changes in paO_2 signify large changes in SaO_2, and O_2 saturation is, therefore, a variable that reacts very sensitively in the case of oxygen deficiency, which means that pulse oximetry is particularly suitable for monitoring oxygen deficiency.
- On the other hand, even with a normal paO_2 of approximately 90–95mmHg virtually all of the hemoglobin is oxygenated
- Monitoring of an upper limit by means of pulse oximetry is no longer conclusive, particularly if the patient is being given oxygen, and transcutaneous blood gas measurement is considered preferable
- Transcutaneous blood gas monitoring is, therefore, most commonly used to avoid hyperoxia in premature infants;
  - Relatively long-term hyperoxia in their case leads to irreversible blindness

Pulse Oximetry

- Pulse oximetry is a noninvasive method for continuously measuring oxygen saturation in arterial blood
- Parameter is not called SaO2 but SpO2, to signify that the oxygen saturation is determined by means of pulse oximetry and to point towards their principal difference



Functional and Fractional Saturation

- The value SpO2 from pulse oximetry is always what is known as *functional* saturation: oxyhemoglobin as percentage of *total functional* hemoglobin which can transport oxygen:

$$SpO_2 = \frac{O_2Hb}{O_2Hb + Hb} \times 100\%$$

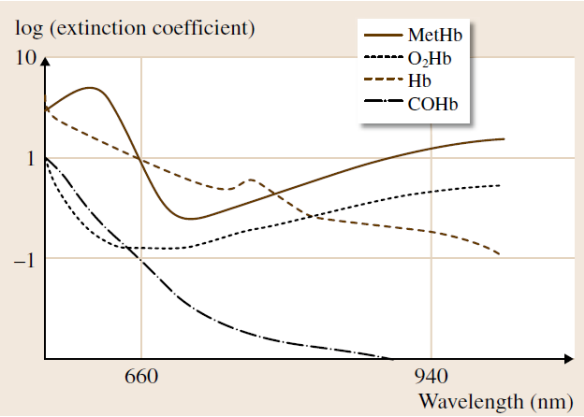
- Fractional saturation is determined using laboratory CO-oximeters is defined as hemoglobin as percentage of total measured hemoglobin including dysfunctional hemoglobin derivatives, e.g. carboxyhemoglobin or methemoglobin:

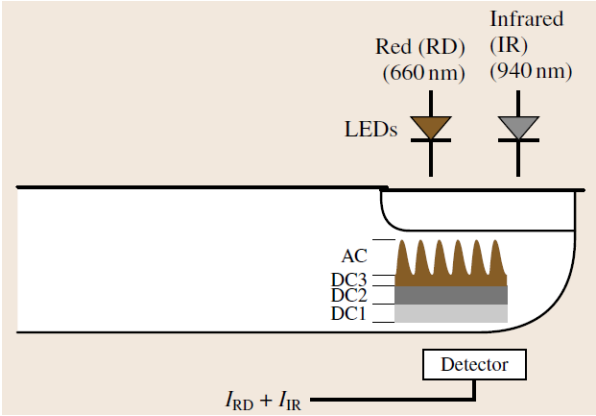
$$SaO_2 = \frac{O_2Hb}{(O_2Hb + Hb + COHb + MetHb)} \times 100\%$$

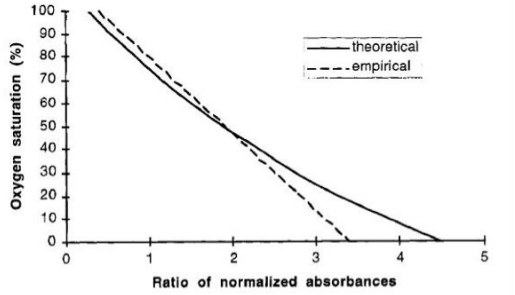
Conventional Pulse Oximetry

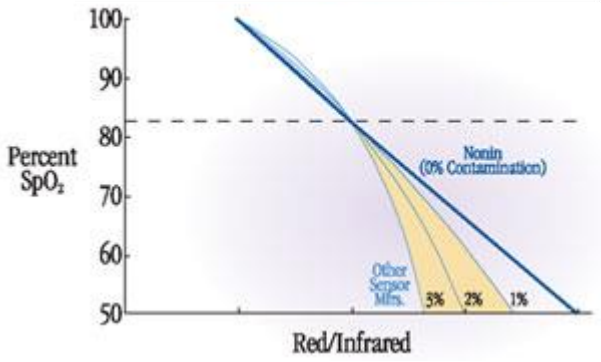
- Based on assumption that only arterial blood has pulsatile AC component of light absorption, whereas tissue, venous blood and nonpulsatile arterial blood always constitute a constant DC
- Intensities IRD and IIR registered by detector thus include AC and DC components in each that can be compared as:

$$r = \frac{I_{RD}\,AC / I_{RD}\,DC}{I_{IR}\,AC / I_{IR}\,DC}$$









Reading Assignment

- Read Chapter 49 of *Springer Handbook of Medical Technology*