Innocor®

INERT GAS REBREATHING METHOD

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1 INERT GAS REBREATHING METHOD

1.1 SCOPE

The purpose of this section is to give an introduction to the Inert Gas Rebreathing Method used in Innocor. This section applies to distributors and end-users of Innocor with only limited experience in gas exchange measurements.

For more detailed information about the rebreathing method, please contact Innovision A/S or simply look in medical article databases.

1.2 INTRODUCTION

Inert Gas Rebreathing is an old technique introduced by August Krogh back in 1912. Since the introduction the method has been validated through numerous medical publications. Despite the indisputable scientific value of the method, inert gas rebreathing has until now only gained little propagation. The main reason is that the equipment required to perform the measurements has been expensive and difficult to maintain.

With the introduction of Innocor, Inert Gas Rebreathing has become a simple and easy-to-use method for measuring important cardiopulmonary parameters. Innocor is a small and portable device and it requires only little maintenance.

This document will enable the reader to understand the cardiopulmonary parameters measured by Innocor and the way they are determined.

1.3 REBREATHING PARAMETERS

The parameters measured by a fully equipped Innocor are:

Symbol	Name	Unit
CO	Cardiac Output (1	l/min
CI	Cardiac Index (1	l/min/m^2
PBF	Pulmonary Blood Flow	l/min
V_L	Lung Volume	l (BTPS)
HR	Heart Rate	1/min
SV	Stroke Volume (1	ml
SI	Stroke Index (1	ml/m^2
VO_2	Oxygen uptake (2	l/min (STPD)
VO_2/kg	Oxygen uptake pr kg body weight (2	ml/min/kg (STPD)
S_pO_2	Oxygen saturation in arterial blood	%
S_vO_2	Oxygen saturation in mixed venous blood (2	%
%A-V O_2	Arterio-venous oxygen saturation difference (2	%
Shunt	Shunt fraction (2	%
SYS	Systolic blood pressure (3	mmHg
DIA	Diastolic blood pressure (3	mmHg
MAP	Mean Arterial blood Pressure (3	mmHg
SVR	Systemic Vascular Resistance (3	mmHg/(l ⁄ min)
SVRI	Systemic Vascular Resistance Index (3	mmHg · m^2/(l ⁄ min)

1) In case of a significant shunt the oxygen sensor option is required to calculate the parameter.
2) Requires the oxygen sensor option.
3) Requires the NIBP option (blood pressure).

All the listed parameters will be explained in detail in this section.

1.4 THE REBREATHING MODEL

Calculations of the cardiopulmonary parameters are based on a single-alveolar lung model, and assumptions included in the model are:

- Complete and instantaneous mixing of all gases in the volume consisting of alveolar and dead space air and bag volume.
- Instantaneous equilibration of the soluble gas between the alveoli and blood, and between alveoli and tissue, respectively.
- Constant pulmonary blood flow (PBF) and constant volume of lung tissue (Vt).
- Negligible mixed venous concentration of soluble gas throughout the rebreathing period. For this assumption to be true, it is required that no recirculation occurs within the rebreathing period, and that repeated determinations are carried out with a sufficient washout period of e.g. 5 minutes in between.

1.4.1 Total systemic volume (Vs,tot)

Inert gas rebreathing allows the total systemic volume to be determined with high accuracy.

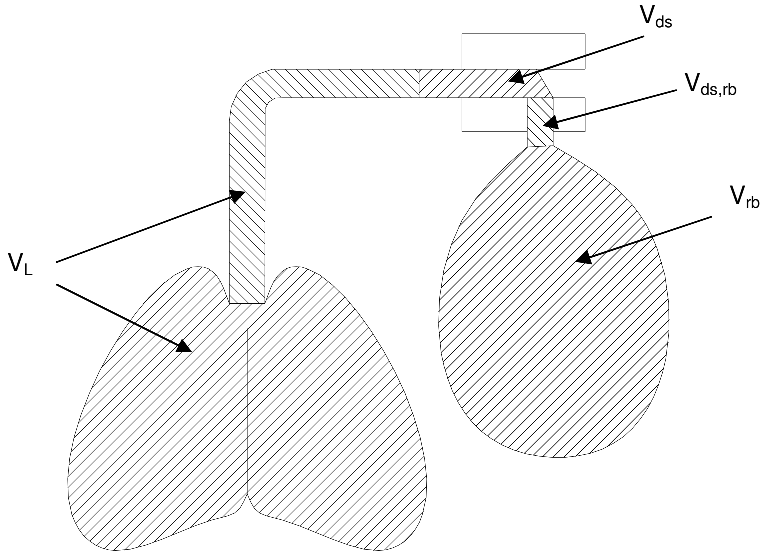


Figure 1.4.1-1 Systemic volumes.

The total systemic volume is defined as:

$$V_{s,tot} = V_L + V_{ds} + V_{ds,rb} + V_{rb}$$

where

V_L = Lung volume at the end of an expiration
V_{ds} = Dead space volume of rebreathing valve (RVU)
$V_{ds,rb}$ = Residual volume of bag when empty
V_{rb} = Volume of rebreathing bag

During the rebreathing period the concentration of insoluble gas (SF_6) decreases from the initial value in the bag (F_i^0) to a final equilibrium ($F_{i,eq}$) value practically obtained after a few breaths (figure 1.4.1-2). Since the volume of the rebreathing bag is known, the total systemic volume can be determined simply from the dilution of the insoluble gas.

A typical SF_6 curve from a rebreathing manoeuvre is shown in figure 1.4.1-2.

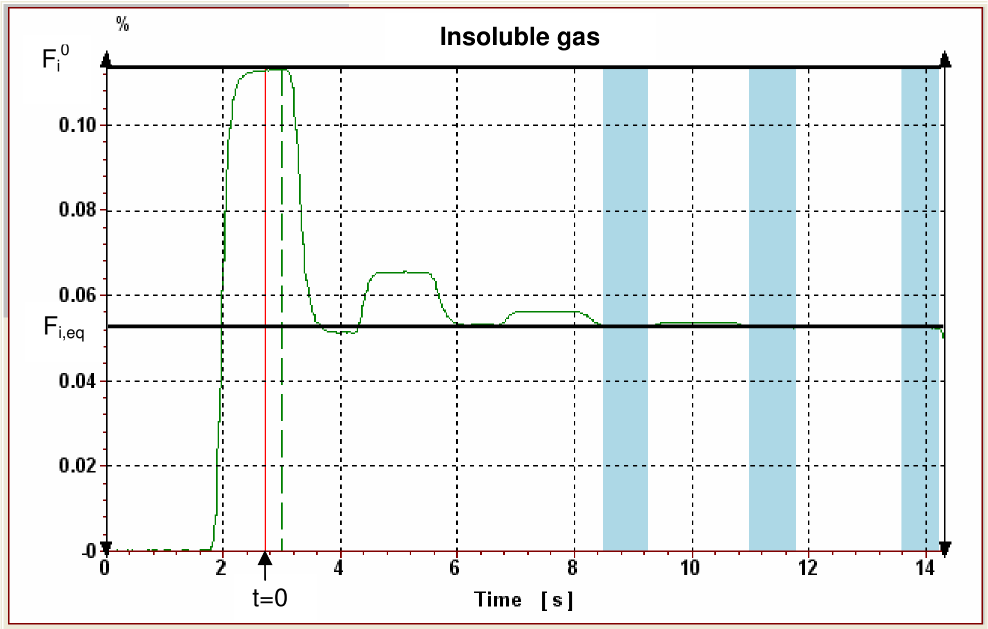


Figure 1.4.1-2 Insoluble gas concentration during rebreathing.

The total systemic volume is not constant during a rebreathing manoeuvre. Initially the volume increases due to a constant oxygen uptake and an increased excretion of carbon dioxide. Normally the rebreathing manoeuvre is performed at slightly forced ventilation. Since the pulmonary blood flow is assumed to be constant, the increased ventilation causes a lower alveolar partial pressure of carbon dioxide. The higher gradient (CO_2) between the alveoli and the capillaries causes a rise in carbon dioxide excretion and hereby also an increase in systemic volume.
The increased excretion of carbon dioxide lasts only short. As the carbon dioxide quickly builds up in the lungs and bag, the gradient between the alveolar and capillary (mixed venous) CO_2 concentrations falls. This decreases the carbon dioxide excretion. The oxygen uptake is still constant. The result is therefore a shrinkage in the total systemic volume.

The total systemic volume, referred to in this document, is the volume at the time “zero”. Time “zero” is defined as the middle of the first inspiration. This volume is difficult to measure directly since the volume measurements require the insoluble gas to be perfectly mixed. At the time zero this is not the case. Therefore the volume is determined by back extrapolation by drawing a straight line through the expiratory points of the insoluble gas where adequate mixing is obtained. The insoluble gas concentration at time “zero” is then determined as the point where the extrapolated line crosses time “zero” - see figure 1.4.1-2 ($F_{i,eq}$).

The total systemic volume at time “zero” is calculated using the following formula:

$$V_{s,tot} = \frac{F_i^0}{F_{i,eq}} \cdot V_{rb}$$

where

$V_{s,tot}$ = Total systemic volume
F_i^0 = Initial concentration of insoluble gas in the rebreathing bag
$F_{i,eq}$ = Equilibrium concentration of insoluble gas (back extrapolated to t = 0)

Example: Total systemic volume

How to calculate the total systemic volume from the data in figure 1.4.1-2:

The following data is assumed:

V_{RB} = 2 l
P_B = 763 mmHg
t_a = 23 ℃
RH = 24%

Data from figure 1.4.1-2:

Initial concentration of SF_6 in the rebreathing bag, $F_i^0 = 0.114\%$
Equilibrium concentration of SF_6, $F_{i,eq} = 0.053\%$ (back extrapolated to t = 0)

The total systemic volume can now be calculated:

$$V_{s,tot}(ATP) = \frac{F_i^0}{F_{i,eq}} \cdot V_{RB}(ATP)$$

where

ATP = Ambient temperature, pressure and humidity

Example:

$$V_{s,tot}(ATP) = \frac{0.114}{0.053} \cdot 2\ \mathrm{l} = 4.30\ \mathrm{l}$$

The $V_{s,tot}$ is converted to STPD (see section 1.4.22) for further calculations:

$$V_{s,tot}(STPD) = \frac{273}{273 + t_a} \cdot \frac{P_B - \frac{RH}{100\%} \cdot P_{H2O}(t_a)}{760} \cdot V_{s,tot}(ATP)$$

Example:

$$V_{s,tot}(STPD) = \frac{273}{273 + 23} \cdot \frac{763 - \frac{24}{100} \cdot 21.1}{760} \cdot 4.30\ \mathrm{l} = 3.96\ \mathrm{l}$$

1.4.2 Pulmonary Blood Flow (PBF)

PBF is the blood flow that perfuses the ventilated part of the alveoli.

During rebreathing an amount of the soluble gas disappears from the alveoli due to solution in tissue and blood. An initial nearly instantaneous disappearance of soluble gas is ascribed to solution of the gas in lung tissue, while the later gradual decrease is due to washout into the blood flowing through the capillaries. Figure 1.4.2-1 shows a typical washout curve for soluble gas (N_2O) during a rebreathing manoeuvre.

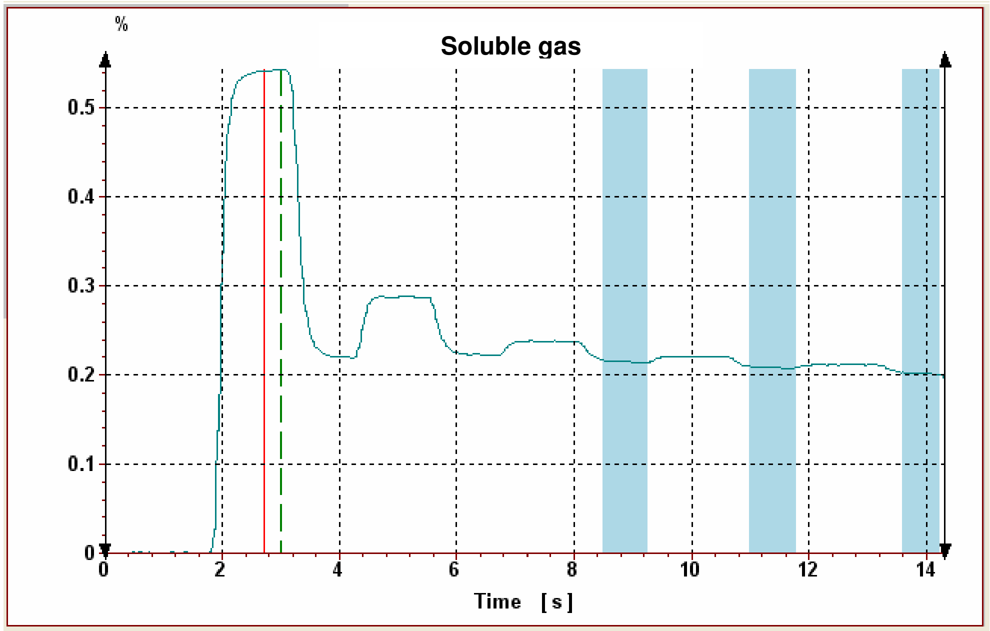


Figure 1.4.2-1 Soluble gas concentration during rebreathing.

The disappearance rate is proportional to the pulmonary blood flow. Assuming a constant PBF and a constant total systemic volume, the disappearance curve for the soluble gas describes a mono-exponentially decreasing function of time, since the rate of absorption is also proportional to the alveolar gas concentration. The exponentially decaying concentration of soluble gas can be represented by a rectilinear disappearance in a semi logarithmic plot. Figure 1.4.2-2 shows a semi logarithmic plot of soluble gas concentrations (normalised) during a rebreathing manoeuvre.

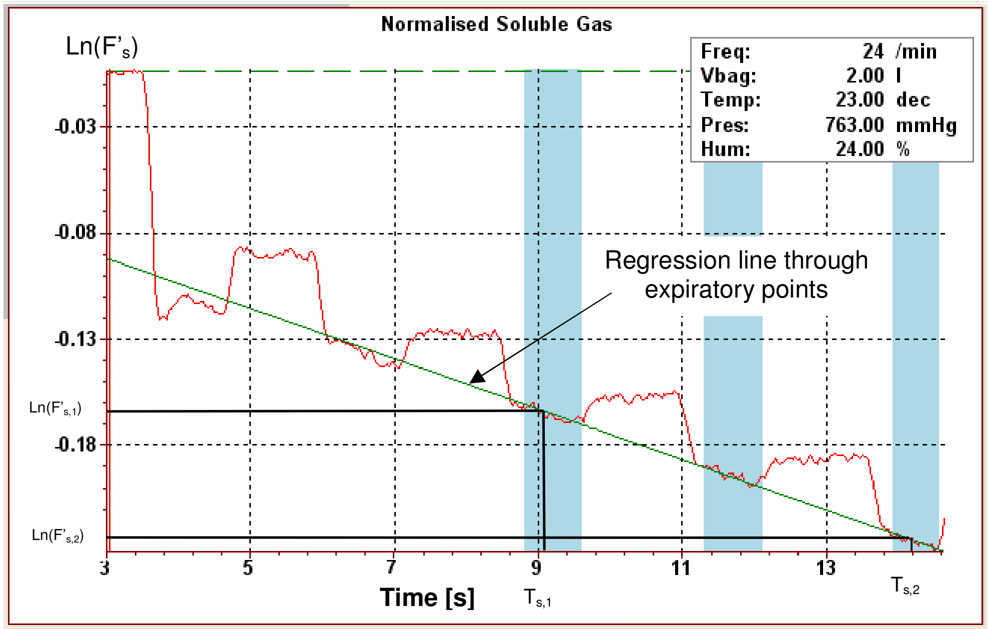


Figure 1.4.2-2 Semilogarithmic plot for soluble gas (N_2O).

The pulmonary blood flow can be calculated using the following formula:

$$PBF = -\beta \cdot \frac{V_{s,tot} \cdot C_1 + C_2}{\alpha_b}$$

where

PBF = Pulmonary Blood Flow
$V_{s,tot}$ = Total systemic volume (STPD)
C_1 = $760/(P_B - 47)$
C_2 = $\alpha_t \cdot V_t$, Constant to account for the disappearance of soluble gas into lung tissue.
α_b = Bunsen solubility coefficient in blood [ml STPD/ml/atm @ 37℃] (α_b,N_2O = 0.412).
α_t = Bunsen solubility coefficient in tissue [ml STPD/ml/atm @ 37℃] (α_t,N_2O = 0.407).
V_t = Lung tissue volume (default 600 ml)
P_B = Ambient pressure in mmHg

As mentioned in section 1.4.1, the total systemic volume shrinkage occurs mainly due to the continuing oxygen uptake and decreasing excretion of carbon dioxide. Therefore, and in order to compensate for incomplete mixing, concentrations of soluble gas are corrected prior to any of the calculations, according to the changes in concentration of insoluble gas (normalisation). The regression line, with slope β (Figure 1.4.2-2), is drawn through the expiratory points of the logarithmic normalised soluble gas concentrations.

β = Slope of line through the expiratory points of:

$$\ln(F'_s(t)) = \ln\left(\frac{F_s(t) \cdot F_i^0}{F_i(t) \cdot F_s^0}\right)$$

where

$F'_s(t)$ = Normalised fractional concentrations of soluble gas
$F_s(t)$ = Fractional soluble gas concentration as a function of time
$F_{i,}^0$ = Initial fractional insoluble gas concentration in the rebreathing bag
$F_i(t)$ = Fractional insoluble gas concentration as a function of time
F_s^0 = Initial fractional concentration of soluble gas in the rebreathing bag

The insoluble gas is hereby used as an indicator of the size of the volume the soluble gas disappears from and to estimate the degree of “incomplete mixing”.

Having the total systemic volume defined, the pulmonary blood flow can be estimated directly from the slope of the regression line shown in figure 1.4.2-2. *“The steeper the slope, the higher the pulmonary blood flow”.*

Example: Pulmonary blood flow:

Estimation of pulmonary blood flow from the data in figure 1.4.2-2:

$$\mathrm{PBF} = -\beta \cdot \frac{V_{s,tot} \cdot C_1 + C_2}{\alpha_b}$$

The slope of the regression line through the expiratory points:

$$\beta = \frac{\ln(F'_{s,2}) - \ln(F'_{s,1})}{T_2 - T_1}$$

From figure 1.4.2-2:

$\ln(F'_{s,2})$ = -0.223
$\ln(F'_{s,1})$ = -0.164
T_2 = 14.2 sec.
T_1 = 9.1 sec.

$$\beta = \frac{-0.223 - (-0.164)}{(14.2 - 9.1)/60} \,/\,\mathrm{min} = -0.694 \,/\,\mathrm{min}$$

Given data:

$V_{s,tot}(\mathrm{STPD})$ = 3.96 l
C_1 = 1.06
C_2 = 0.600 • 0.407 l = 0.244 l
α_b = 0.412

$$\mathrm{PBF} = -(-0.694) \cdot \frac{3.96 \cdot 1.06 + 0.244}{0.412} \,\mathrm{l/min} = 7.45\ \mathrm{l/min}$$

1.4.3 Oxygen uptake (Vo_2)

With the Oxygen Analyser option included, it is possible to measure oxygen uptake.

The measurement is based on the assumption that the alveolar partial pressure of O_2 is higher than 100 mmHg throughout the rebreathing period so that the blood perfusing the ventilated alveoli is fully saturated with oxygen. Figure 1.4.3-1 shows an oxygen-rebreathing curve.

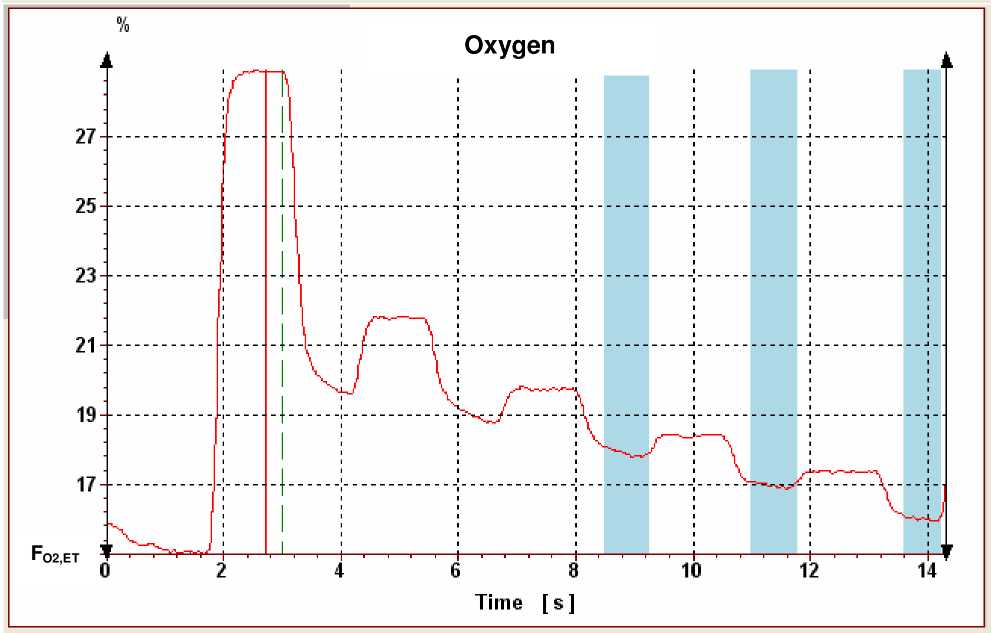


Figure 1.4.3-1 Oxygen rebreathing curve.

If the oxygen uptake, VO_2, during the rebreathing period is constant, the slope of the disappearance curve for O_2 is proportional to the oxygen uptake:

$$Vo_2 = -\beta \cdot V_{s,tot}\,(STPD)$$

where

$V_{s,tot}$ = Total systemic volume (STPD)

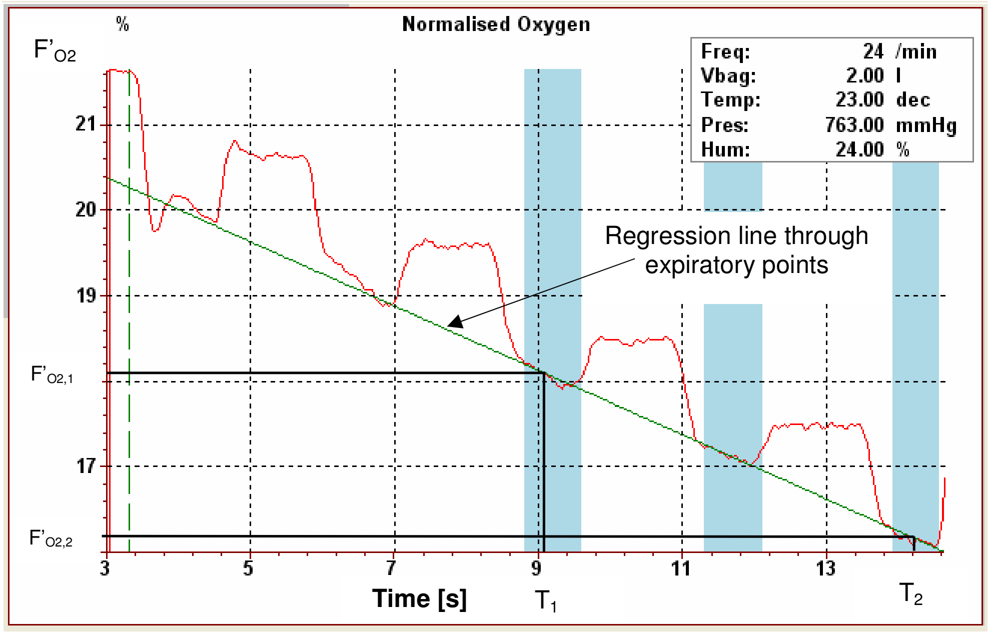
Due to the volume shrinkage, and in order to compensate for incomplete mixing, concentrations of oxygen are corrected prior to any of the calculations, according to the changes in concentration of insoluble gas (normalisation). The regression line, with slope β (Figure 1.4.3-2), is drawn through the expiratory points of the normalised oxygen concentrations.

β = Slope of line through the expiratory points of:

$$F'_{O2}(t) = \left(F_{O2}(t) - F_{O2,ET}\right) \cdot \frac{F_{i,eq}}{F_i(t)} + F_{O2,ET}$$

where

$F'_{O2}(t)$ = Normalised fractional concentrations of oxygen
$F_{O2}(t)$ = Fractional oxygen concentration as a function of time
$F_{O2,ET}$ = End-tidal fractional oxygen concentration prior to rebreathing
$F_{i,eq}$ = Equilibrium concentration of insoluble gas (back extrapolated to t = 0)
$F_i(t)$ = Fractional insoluble gas concentration as a function of time



Freq: 24 /min
Vbag: 2.00 l
Temp: 23.00 dec
Pres: 763.00 mmHg
Hum: 24.00 %

Figure 1.4.3-2 Oxygen rebreathing curve, normalised.

Example: Oxygen uptake

Oxygen uptake calculated from the data in figure 1.4.3-2.

The slope of the regression line through the expiratory points:

$$\beta = \frac{F'_{O2,2} - F'_{O2,1}}{T_2 - T_1}$$

From figure 1.4.3-2:

$F'_{O2,2}$ = 0.162
$F'_{O2,1}$ = 0.181
T_2 = 14.2 sec.
T_1 = 9.1 sec.

$$\beta = \frac{0.162 - 0.181}{(14.2 - 9.1)/60} \, / \sec = -0.224 \, / \sec .$$

Given data:

$V_{s,tot}$(STPD) = 3.96 l.

Result:

V_{O_2} = -(-0.224) · 3.96 l/min = 0.89 l/min

1.4.4 Oxygen uptake pr kg body weight (Vo_2/kg)

The oxygen uptake in proportion to body weight:

$$Vo_2 / kg = 1000 \cdot \frac{Vo_2}{Weight} \quad \text{[ml/min/kg]}$$

Example:

Weight = 75 kg

Vo_2/kg = 1000 · 0.89 / 75 = 11.9 ml/min/kg

1.4.5 Lung Volume (V_L)

In the literature FRC is defined as the gas volume in the lungs at the end of expiration (at rest). In stress test and in measurements at rest with increased ventilation (for better mixing) the measured V_L is not the "true FRC" but rather something between the Functional Residual Capacity (FRC) and Residual Volume (RV). Residual volume is the volume left in the lungs after a maximal expiratory effort.

The V_L can be determined by the equation from section 1.4.1:

$$V_L = V_{s,tot} - (V_{rb} + V_{ds,rb} + V_{ds})$$

When BTPS, STP and STPD conditions are used the equation becomes:

$$V_L(BTPS) = [V_{s,tot}(STPD) - (V_{rb}(ATP) + V_{ds,rb}(ATP)) \cdot C_1] \cdot C_2 - V_{ds}(BTPS)$$

where

$V_{s,tot}$ = Total systemic volume, STPD

V_{rb} = Volume of rebreathing bag, ATP

V_{ds} = Dead space volume of rebreathing valve (RVU), BTPS (containing expired air)

$V_{ds,bag}$ = Residual volume of bag when empty, ATP

C_1 = Conversion from ATP to STPD, see section 1.4.22

C_2 = Conversion from STPD to BTPS, see section 1.4.22

Example:

$V_{s,tot}(STPD)$ = 3.96 l

$V_{rb}(ATP)$ = 2 l

$V_{ds,rb}(ATP)$ = 0.013 l

$V_{ds}(BTPS)$ = 0.102 l

P_B = 760 mmHg

t_a = 23 °C

RH = 24%

$$C_1 = \frac{273}{273+23} \cdot \frac{763 - \frac{24}{100} \cdot 21.1}{760} = 0.916$$

$$C_2 = \frac{273+37}{273} \cdot \frac{760}{763-47} = 1.205$$

$$V_L(BTPS) = (3.96 - (2.0+0.013) \cdot 0.916) \cdot 1.205 - 0.102 \text{ l} = 2.45 \text{ l}$$

1.4.6 Arterial Oxygen Saturation (%S_pO_2)

The oxygen saturation of haemoglobin in arterial blood (%S_pO_2) is determined by pulse oximetry.

Oxygen saturation is determined by the pulse oximeter as an estimate of the proportion of haemoglobin which is present in a reduced form by comparing the absorption of infrared light at two different wavelengths where the absorption for oxygenated and reduced haemoglobin is the same and very different, respectively.

1.4.7 Cardiac Output (CO)

Cardiac Output (CO) is defined as the output of the left ventricle pr unit time. The CO is not necessary equal to the PBF, which is the blood flow that perfuses the ventilated part of the alveoli. The difference is the Shunt flow, Q'_s – see figure 1.4.7-1.

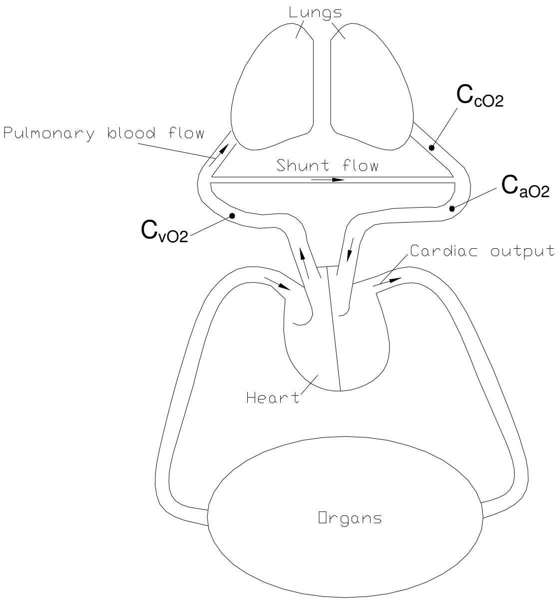


Figure 1.4.7-1 CO, PBF and shunt flow.

Three equations can be written.

Based on simple mass conservation:

$$CO = PBF + Q'_s \qquad (1)$$

where

CO = Cardiac Output [l/min]
PBF = Pulmonary blood flow
Q'_s = Shunt flow [l/min]

From Fick's principle:

$$CO = \frac{Vo_2}{C_{aO2} - C_{vO2}} \qquad \text{[l/min]} \qquad (2)$$

where

C_ao_2 = Oxygen content in arterial blood [litres STPD/litre]

C_ao_2 = $0.000139 \cdot Hb \cdot \%S_PO_2$
$\%S_po_2$ = Arterial oxygen saturation [%], as defined in section 1.4.6
Hb = Haemoglobin concentration [g/dl]
C_{vO2} = Oxygen content in mixed venous blood
VO_2 = Oxygen uptake [l/min]

Fick's principle used on the pulmonary circulation:

$$PBF = \frac{Vo_2}{C_{cO_2} - C_{vO_2}} \quad \text{[l/min]} \qquad (3)$$

where

C_co_2 = Oxygen content in end-capillary blood [litres STPD/litre]
C_co_2 = $0.000139 \cdot Hb \cdot \%S_Co_2$
$\%S_co_2$ = End-capillary oxygen saturation [%]
$\%S_co_2$ = 98% (assumed)

The three equations contain three unknown parameters (CO, Q'_s and C_vo_2) and can be solved as:

$$CO = \frac{1}{\frac{1}{PBF} + \frac{C_aO_2 - C_cO_2}{Vo_2}}$$

Example:

PBF = 7.45 l/min
$\%S_po_2$ = 97 %
Hb = 15 g/dl
C_ao_2 = $0.000139 \cdot 15 \cdot 97 = 0.2022$
C_co_2 = $0.000139 \cdot 15 \cdot 98 = 0.2043$
Vo_2 = 0.89 l/min

$$CO = \frac{1}{\frac{1}{7.45} + \frac{0.2022 - 0.2043}{0.89}} \, l/\min = 7.58 \, l/\min$$

The calculation of cardiac output and shunt requires that both the pulse oximeter (Spo_2) and Oxygen Analyser (Vo_2) are installed and used.

1.4.8 Shunt fraction

The shunt fraction is defined as the proportion between the shunt flow and the total blood flow from the left ventricle (see figure 1.4.7-1):

$$\text{Shuntfraction} = \frac{Q'_s}{CO} \cdot 100\%$$

where

Q'_s = Shunt flow [l/min]
CO = Cardiac Output [l/min]

If the cardiac output is known (see section 1.4.7), the shunt fraction can be calculated using the formula:

$$\frac{Q'_s}{CO} = \left(1 - \frac{PBF}{CO}\right) \cdot 100\%$$

where

PBF = Pulmonary Blood Flow

Example:

PBF = 7.45 l/min
CO = 7.58 l/min
Shuntfraction = (1 – 9.0/9.38) · 100% = 1.7%

1.4.9 Mixed venous oxygen saturation ($\%S_vO_2$)

The mixed venous oxygen saturation is the oxygen saturation of haemoglobin in mixed venous blood returning to the lungs for oxygenation. The calculation of $\%S_vO_2$ is based on the $\%S_cO_2$, Vo_2, PBF and Hb:

$$\%S_vO_2 = \%S_CO_2 - \frac{Vo_2}{PBF \cdot 0.000139 \cdot Hb} \quad [\%]$$

where

$\%S_cO_2$ = End-capillary oxygen saturation [%]
$\%S_cO_2$ = 98% (assumed)
Vo_2 = Oxygen Uptake [l/min]
PBF = Pulmonary blood flow [l/min]
Hb = Haemoglobin concentration [g/dl]

Example:

$\%S_cO_2$ = 98%
Vo_2 = 0.89 l/min
PBF = 7.45 l/min
Hb = 15 g/dl

$$\%S_vO_2 = \left(98 - \frac{0.89}{7.45 \cdot 0.000139 \cdot 15}\right)\% = 41\%$$

1.4.10 %A-V oxygen difference (%A-V O_2)

The %A-V oxygen difference is the difference in oxygen saturation in arterial blood compared to mixed venous blood:

$$\%\text{A-V } O_2 = \%S_pO_2 - \%S_vO_2 \qquad [\%]$$

Example:

$$\%\text{A-V } O_2 = (97 - 41)\% = 56\%$$

1.4.11 Heart Rate (HR)

The number of heart beats per minute.
Measuring HR requires only the standard pulse oximeter.
Calculated as 1/RR, where RR is the peak-peak interval determined from a pulse oximeter plethysmogram.

1.4.12 Body Surface Area (BSA)

The total surface area of the body is used to calculate indices. BSA is calculated from the equation:

$$BSA = 0.007184 \cdot W^{0.425} \cdot H^{0.725}\ [m^2]$$

where

W = Weight of patient [kg]
H = Height of patient [cm]

Example:

W = 75 kg
H = 175 cm
BSA = $0.007184 \cdot 75^{0.425} \cdot 175^{0.725}\ m^2 = 1.90\ m^2$

The data is taken from the patient database. If patient’s height and weight are not typed into the database, the indices will not be calculated.

1.4.13 Cardiac Index (CI)

Cardiac Index is defined as the amount of blood ejected from the left ventricle into the aorta (systemic circulation) per unit time seen in proportion to body size (surface area):

$$CI = \frac{CO}{BSA}\left[\frac{l}{\min \cdot m^2}\right]$$

where

CO = Cardiac Output [l/min]
BSA = Body Surface Area [m^2]

Example:

CO = 7.58 l/min
BSA = 1.90 m^2
CI = 9.38/1.90 l/min/m^2 = 3.99 l/min/m^2

1.4.14 Stroke Volume (SV)

Stroke volume [ml] is defined as the amount of blood ejected by the left ventricle into the aorta per heart beat.

$$\mathrm{SV} = \frac{\mathrm{CO}}{\mathrm{HR}} \cdot 1000 \text{ [ml]}$$

where

CO = Cardiac Output [l/min]
HR = Heart Rate [1/min]

Example:

CO = 7.58 l/min
HR = 73 /min
SV = 7.58/73·1000 ml = 104 ml

1.4.15 Stroke Index (SI)

The stroke volume in proportion to the body surface area (BSA):

$$\mathrm{SI} = \frac{\mathrm{SV}}{\mathrm{BSA}} \text{ [ml/m}^2\text{]}$$

Example:

SV = 104 ml
BSA = 1.90 m^2
SI = 104/1.90 ml/m^2 = 54.7 ml/m^2

1.4.16 Blood Pressure (DIA, SYS, MAP)

If the NIBP option is included, the blood pressure parameters can be measured [mmHg].

The diastolic blood pressure (DIA) is defined as the lowest pressure during diastole.

The systolic blood pressure (SYS) is defined as the highest pressure during systole.

The mean arterial blood pressure (MAP) is calculated by the NIBP module, but can be estimated from the systolic and diastolic blood pressures:

$$\mathrm{MAP} = \mathrm{DIA} + \frac{(\mathrm{SYS} - \mathrm{DIA})}{3} \text{ [mmHg]}$$

1.4.17 Systemic Vascular Resistance (SVR)

The resistance to blood flow in the systemic blood circulation, i.e. the average resistance that the left ventricle works against when delivering the stroke volume into the aorta.

$$\mathrm{SVR} = \frac{\mathrm{MAP} - \mathrm{CVP}}{\mathrm{CO}} \left[\frac{\mathrm{mmHg}}{\mathrm{l/min}}\right]$$

where

MAP = Mean Arterial Pressure [mmHg]
CVP = Central Venous Pressure [mmHg]
As CVP is not measured it is set to 4.6 mmHg by default.
CO = Cardiac Output [l/min]

Example:

MAP = 113 mmHg
CO = 7.58 l/min
SVR = (113-4.6)/7.58 mmHg/(l/min) = 14.3 mmHg/(l/min)

1.4.18 Systemic Vascular Resistance Index (SVRI)

The resistance to blood flow in the systemic blood circulation seen in proportion to body surface area

$$SVRI = \frac{MAP - CVP}{CI} = \frac{(MAP - CVP) \cdot BSA}{CO} \left[\frac{mmHg \cdot m^2}{l/\min}\right]$$

where

MAP = Mean Arterial Pressure [mmHg]
CVP = Central Venous Pressure [mmHg]
As CVP is not measured it is set to 4.6 mmHg by default.
CI = Cardiac Index [l/min/m^2]
CO = Cardiac Output [l/min]
BSA = Body Surface Area [m^2]

Example:

MAP = 113 mmHg
CO = 7.58 l/min
SVR = 14.3 mmHg/(l/min)
BSA = 1.90 m^2
SVRI = (113-4.6)·1.90/7.58 mmHg·m^2/(l/min) = 27.2 mmHg·m^2/(l/min)

1.4.19 Cardiac Power Output (CPO)

Cardiac Power Output is a measurement of the cardiac pumping capability.

CPO = CO · MAP · 0.0022 [watt]

where

CO = Cardiac Output [l/min]
MAP = Mean Arterial blood Pressure [mmHg]

Example:

MAP = 113 mmHg
CO = 7.58 l/min
CPO = 7.58 · 113 · 0.0022 Watt = 1.88 Watt

1.4.20 Cardiac Power Index (CPI)

Cardiac Power Index is a measurement of the cardiac pumping capability seen in proportion to body size (surface area).

$$CPI = CI \cdot MAP \cdot 0.0022\ [W/m^2]$$

where
CI = Cardiac Index $[l/min/m^2]$
MAP = Mean Arterial blood Pressure [mmHg]

Example:
CI = $3.99\ l/min/m^2$
MAP = 113 mmHg
CPI = $3.99 \cdot 113 \cdot 0.0022\ W/m^2 = 0.99\ W/m^2$

1.4.21 Haemoglobin Concentration (Hb)

Hb is the haemoglobin concentration in blood. The parameter is determined by an analysis of a blood sample. The unit can either be in [g/dl] or in [mmol/l].

1 g/dl = 0.62 mmol/l
1 mmol/l = 1.61 g/dl

A normal value is 7-10 mmol/l for female and 8-11 mmol/l for male subjects.

1.4.22 Conversion between ATP, STPD and BTPS

The volume of a number of moles (n) of gas molecules depends on the thermodynamic temperature (T) and the ambient pressure (P). The following relationship holds for dry gas:

$V = n \cdot R \cdot T/P$

where R = gas constant, and T is expressed in Kelvin (K = 273.2 + ºC).

Air and expired gas are made up of gas molecules and water vapour. In a gas mixture saturated with water vapour and in contact with water (such as occurs in the lung) the number of water molecules in the gas phase varies with temperature and pressure. As the number of molecules is not constant, the above gas law should be applied to dry gas. This also holds outside the lung when gas saturated with water vapour is compressed or cools down.

BTPS:	In respiratory physiology lung volumes and flows are standardised to barometric pressure at sea level, body temperature, saturated with water vapour: body temperature and pressure, saturated.
ATPS:	Measured at ambient temperature, pressure, saturated with water vapour (e.g. expired gas, which has cooled down): ambient temperature and pressure, saturated.
ATP:	Like ATPS, but not saturated with water vapour (e.g. room air).
ATPD:	Like ATPS, but dry (e.g. from a gas bottle).
STPD:	Oxygen consumption and carbon dioxide delivery are standardised to standard temperature (0 ºC), barometric pressure at sea level (101.3 kPa / 760 mmHg) and dry gas: standard temperature and pressure, dry.

Correction from ATP to STPD. Multiply the ATP-value by:

$$\frac{273}{273 + t_a} \cdot \frac{P_B - \frac{RH}{100} \cdot P_{H2O}(t_a)}{760}$$

Correction from BTPS to STPD. Multiply the BTPS-value by:

$$\frac{273}{273 + 37} \cdot \frac{P_B - 47}{760}$$

where

t_a = ambient temperature in °C

P_B = barometric pressure in mmHg

RH = relative humidity in %

$P_{H2O}(t_a)$ = saturated water vapour pressure in mmHg at temperature t_a, see table below

Temperature [°C]	Water vapour pressure [mmHg]
0	4.7
1	5.2
2	5.6
3	6.1
4	6.5
5	7.0
6	7.4
7	7.9
8	8.3
9	8.8
10	9.2
11	9.8
12	10.5
13	11.2
14	12.0

Temperature [°C]	Water vapour pressure [mmHg]
15	12.8
16	13.6
17	14.5
18	15.5
19	16.5
20	17.5
21	18.7
22	19.8
23	21.1
24	22.4
25	23.8
26	25.2
27	26.7
28	28.3
29	30.0

Temperature [°C]	Water vapour pressure [mmHg]
30	31.8
31	33.7
32	35.7
33	37.7
34	39.9
35	42.2
36	44.6
37	47.1
38	49.7
39	52.4
40	55.3