MEASUREMENT of RESPIRATORY SYSTEMS

Lecture Notes

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Respiratory Function Measurements

The respiratory system includes the nose, pharynx, trachea, bronchi and lungs.

1. *Ventilation* : deals with measuring the volume and the speed of the air moved by the body acting as a pump.

2. *Distribution* : provides an indication of where gas flows in the lungs and whether or not disease has closed some sections to air flow.

3. *Diffusion* : tests the ability of lungs to exchange gas with the circulatory system.

Clinical Practice

1. *Pulmonary function tests* : performed at long time scales to determine a subject's parameter values compared to a healthy or diseased population.

2. *Patient monitoring* : performed at very short time scales in ICU.

Respiration Rate

The total amount of air entering the lungs each minute is 12-15 per min for an adult.

Both elastic and inertial forces are involved in expanding the lungs and these forces can balance at a certain resonant frequency when minimum work is expended.

If the inertial component of the lungs has mass m and the elastic component by a coefficient E, then
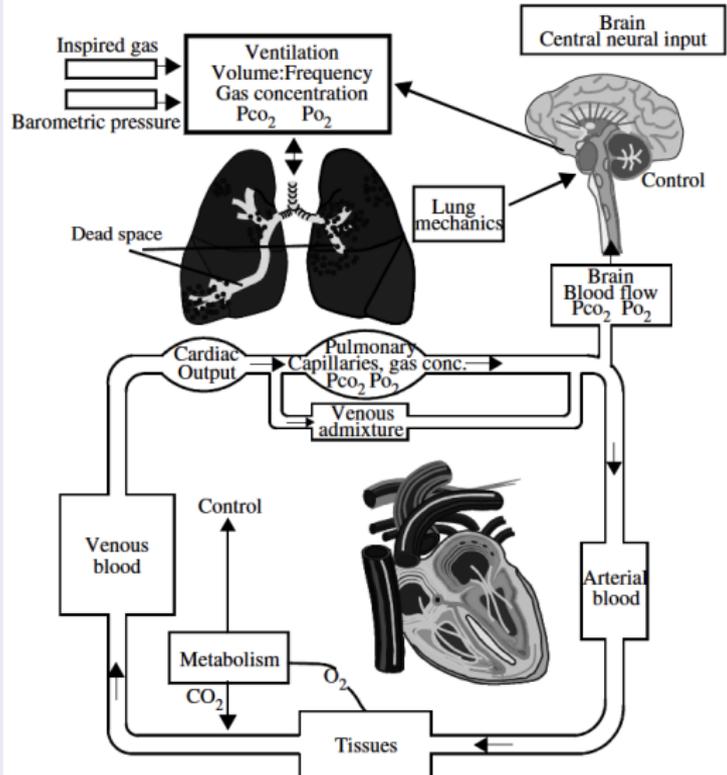
$$m\ddot{x} + Ex = 0$$

the resonant frequency :

$$\frac{1}{2\pi}\sqrt{\frac{E}{m}}$$
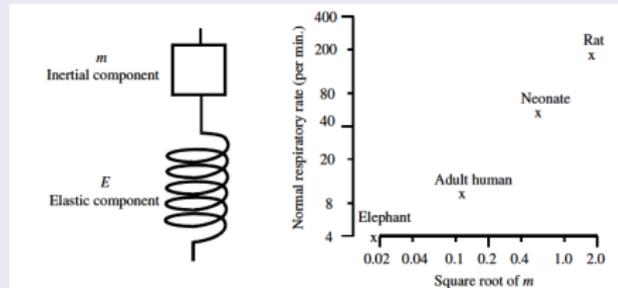
Respiratory Control System

Medulla:
- Control centre for breathing.
- Sensitive to CO_2 level in the blood.
- Controls nerves to respiratory muscles and the diaphragm.
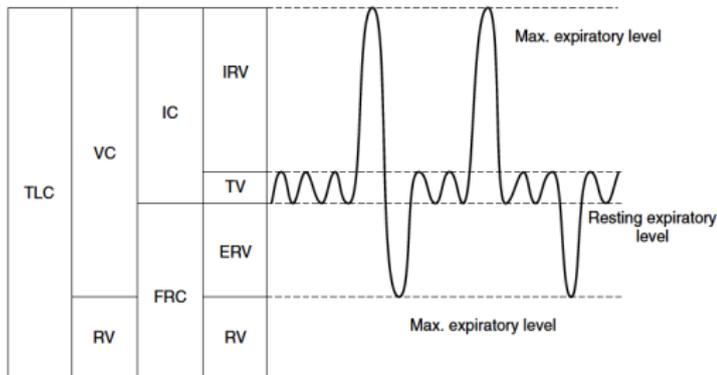- Changes respiration rate and tidal volume.

Respiratory Volumes

Tidal Volume (TV):
Volume of gas inspired
or expired during
normal breathing.
Minute Volume (MV):
Volume of gas exchanged
per minute during
breathing. It is equal to
tidal volume multiplied
by breathing rate.

Alveolar Ventilation (AV): Volume of fresh air entering the alveoli with each breath.

$$AV = \text{Breathing rate} \times (\text{Tidal volume-Dead space})$$

*Inspiratory Reserve Volume (IRV)*: The volume of gas inspired from a normal end tidal volume.

$$IRV = TLC - (TV + FRC)$$

Expiratory Reserve Volume (ERV): The volume of gas remaining after a normal expiration less the volume remaining after a forced expiration.

$$ERV = FRC - RV$$

Residual Volume (RV): The volume of gas remaining in the lungs after a forced expiration.

Respanratory Capacities
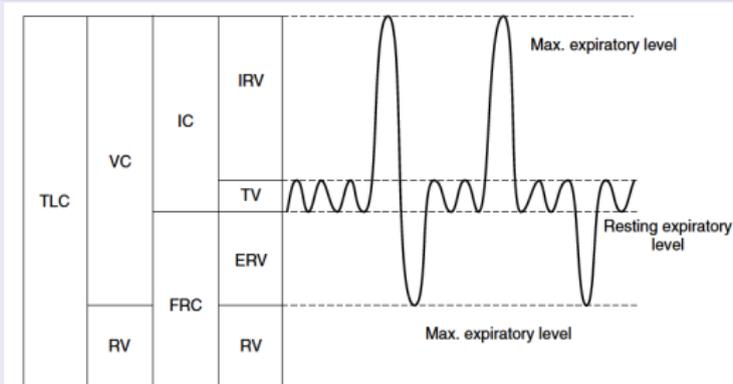
Functional Residual Capacity (FRC): The volume of gas remaining in the lungs after normal expiration.

Total Lung Capacity (TLC): The volume of gas in the lungs at the point of maximal inspiration.

$$TLC = VC + RV$$

Vital Capacity (VC): The greatest volume of gas that can be inspired by voluntary effort after maximum expiration, irrespective of time.

Inspiratory Capacity (IC): The maximum volume that can be inspired from the resting end expiratory position.

Dead Space: Dead Space is the functional volume of the lung that does not participate in gas exchange.

Dynamic Respiratory Parameters

A number of forced breathing tests to assess the muscle power associated with breathing and airway resistance:

Forced Vital Capacity (FVC): Total amount of air that can be forcibly expired as quickly as possible after taking the deepest possible breath.

Forced Expiratory Volume (FEV): The percentage of VC that can be forced out of the lungs in a given period with maximal exertion. This is written as *FEVT* where T is in seconds.

Forced expired vital capacity

Maximum Mid-Expiratory Flow (MMEF) or *Maximum Mid-Flow Rate (MMFR)*: The maximum rate of flow of air during the middle half of the FEV spirogram. One half VC is obtained from the volume indicated by the curve between 25% and 75%.

Mid-Expiratory Time (MET): It is the time in seconds over which this volume is forcibly exhaled.

$$MMEF = (1/2VC) \times (1/MET)$$
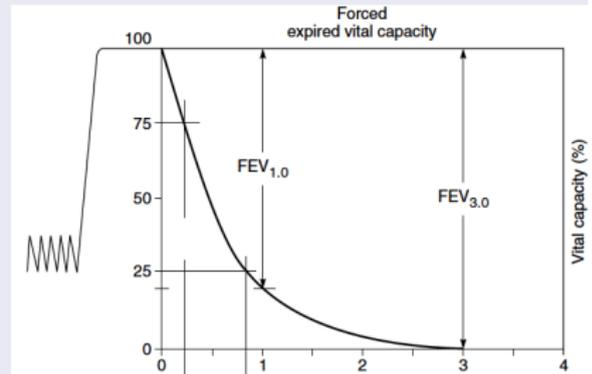
If FEV1/FVC *i.e.* the volume of gas that can be exhaled forcibly in one second from maximum inspiration to the forced vital capacity < 70%, airway has an *obstructive* problem.
If FEV1/FVC > 85%, it indicates a *restrictive* problem.

Pulmonary Function Tests

1 *Single Breath*
   i) Tests that measure expired volume only.
   ii) Tests that measure expired volume in a unit time.
   iii) Tests that measure expired volume/time.

2 *Multiple-breath*
   Maximal Voluntary Ventilation (MVV) : The patient breathes in and out for 15 s as hard and as fast as possible. Total volume of the gas moved is recorded and multiplied by 4 to produce the maximum volume breathed per minute voluntarily.

Spirometry

Spiro is the Latin word meaning breath.

Air breathed into the chamber cause a change in volume inside which is translated into vertical motion and recorded.

It is a mechanical integrator: input is air flow and the output is volume displacement.

It must have a fast response time with a flat frequency response up to 12 Hz.

Problems of inertia and possible oscillation of the bell can lead to an over-estimation of the expiratory volume.

Unless ultralight weight bell is provided, it responds to slow respiratory rates and not to rapid breathing.

The frequency response of a spirometer must be adequate for the measurement of the forced expiratory volume.

The instrument should have no hysteresis, *i.e.* the same volume should be reached whether the spirometer is being filled or being emptied to that volume.
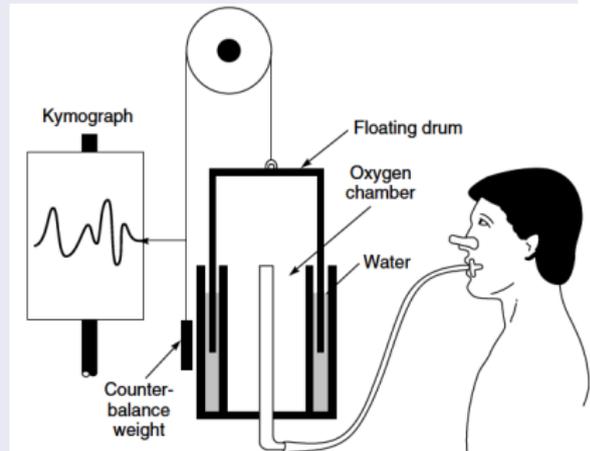
Ultrasonic Spirometer

Gas flowmeters operate in
in the range [40-200] kHz.
At frequencies higher than
200 kHz absorption losses in
the gas are very high,
sounds below 40 kHz are
audible and can be irritating.
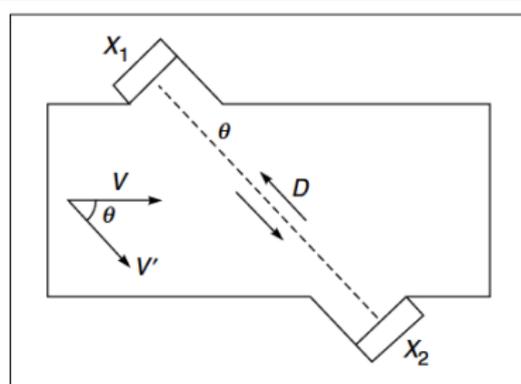
Pulse transit time: upstream, t_1, and downstream, t_2

$t_1 = \frac{D}{C-v'}$ and $t_2 = \frac{D}{C+v'}$

D : distance between transducers

C : velocity of sound propagation in fluid

v' : fluid velocity vector along the path of the pulses.

Average gas velocity $v' = \bar{v}\cos(\theta)$

$f_2 - f_1 = \frac{1}{t_2} - \frac{1}{t_2} = \frac{C+v'}{D} - \frac{C-v'}{D} = \frac{2v'}{D} = \frac{2\bar{v}\cos(\theta)}{D}$

Flow velocity $\bar{v} = \frac{D}{2\cos(\theta)}\left[\frac{1}{t_2} - \frac{1}{t_2}\right] = \frac{D}{2\cos(\theta)}(f_2 - f_1)$

Pneumotachography

Pneumo comes from Greek and means lungs. *Tacho* is a Greek word for speed

Pneumotachograph measures the instantaneous speed of airflow into or out of the lungs.

1. Differential manometer: It has a small resistance, which allows flow but causes a pressure drop. This change is measured by a differential pressure transducer, which outputs a signal proportional to the flow according to the Poiseuille law *i.e.* $\Delta P = \frac{8\mu LF}{\pi R^4}$.

2. Hotwire anemometer: It uses a small heated element in the pathway of the gas flow. The current needed to maintain the element at a constant temperature is measured and it increases proportionally to the gas flow that cools the element.

Pneumotachometer is used to measure parameters pertaining to pulmonary function as forced expiratory volume (FEV), maximum mid-expiratory volume, peak flow and to generate flow-volume loop (flow *vs* volume curve).

It can also be used to derive absolute volume changes of the lung (spirometry) by electronically integrating the flow signal.

They should have a very small resistance to breathing *i.e.* between 0.5-1.0 cm H_2O s/l.

They should have a flat response up to 10 Hz to follow normal respiratory phenomenon.

The dead space volume of the flow head should be as small as possible.
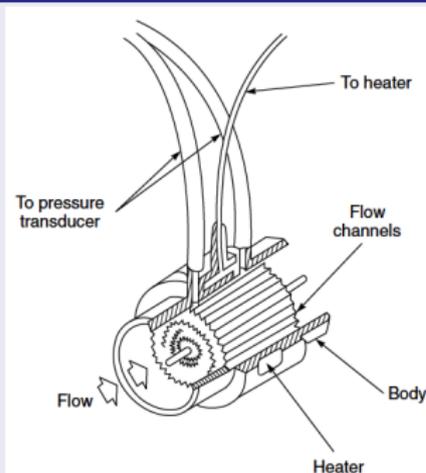
Fleisch-type Pneumotachometer

Resistance elements are
small, parallel metal channels.
The pressure drop across
the element is proportional
to the flow rate of a gas passing
through it.
Differential pressure as the output of
flow transducer is converted into an
electrical signal by a capacitance
type pressure transducer.
To prevent condensation,
the temperature of pneumotach
is maintained at 37°C.

A Fleisch pneumotachometer has 100 capillary tubes, each with a diameter of 1 mm
and a length of 5 cm. What pressure drop occurs for a flow of 1 liters/s?

A flow of 1 liters/s through 100 tubes 10^{-5}m^3/s. $r = \frac{1}{2} = 0.5$mm.

$\Delta P = RF = \frac{8\eta LF}{\pi r^4} = \frac{8 \cdot 1.8 \cdot 10^{-5} \cdot 5 \cdot 10^{-2} \cdot 10^{-5}}{\pi (5 \cdot 10^{-4})^4} = 367$Pa $= 3.74$cm H_2O
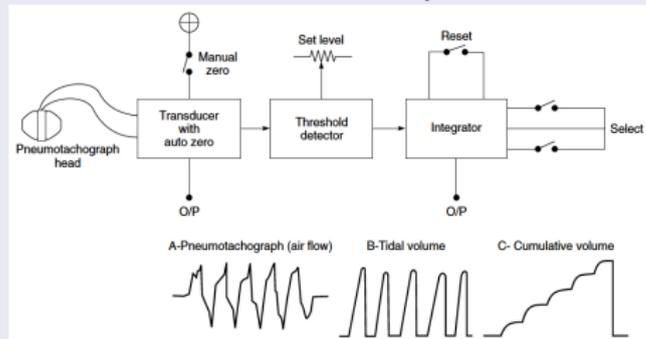
Measurement of Volume

Flow rate can be derived from pressure change across a pneumotachograph head with a micromanometer whose output is a voltage proportional to the pressure difference at the input.

$V_i = K(P_1 - P_2)$
K : a constant
V_1 is integrated to yield
$V_o = \frac{1}{RC} \int\limits_{t_1}^{t_2} V_i dt$

A-Pneumotachograph (air flow)   B-Tidal volume   C- Cumulative volume

The threshold detector selects which portion of the flow signal is to be integrated and this is normally set to switch on when the flow signal moves past zero in a positive direction, and off again when the flow signal returns to zero. When it is intended to measure tidal volume, the flow signal moves positive and continues until the flow output returns to zero, when the integrator output is reset. If not, then cumulative volume is measured.

Flow-Volume Curve

It is a plot of instantaneous maximum expiratory flow rate *vs* volume.

MIF50% :
maximum inspiratory
flow at 50% of vital
capacity.
A useful indicator of
obstruction is the ratio
of MEF50% to MIF50%.
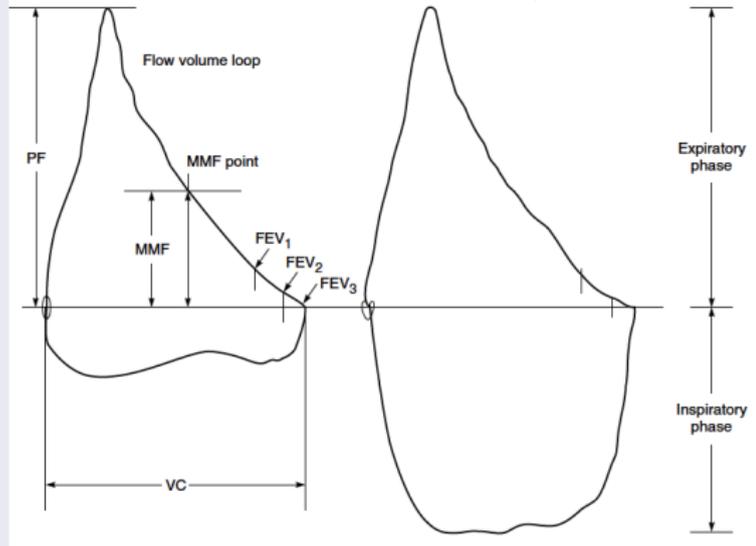
Nitrogen Washout Estimate of Lung Volume

Subject inhales N_2 free gas
but exhales N_2 with O_2
and CO_2.
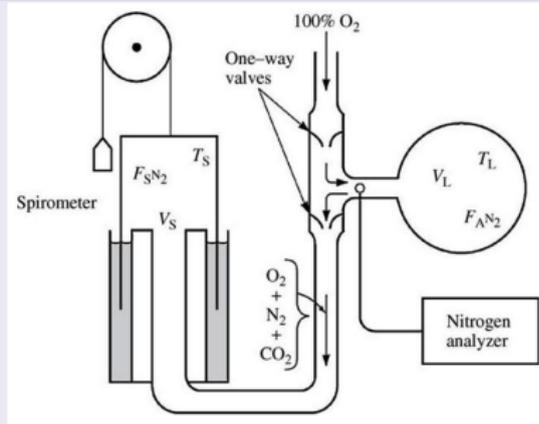7 to 10 min. respiration
with constant tidal volume.
Static mass balance :
F : Molar fraction of a gas
$$F_{A,N_2}(t_1)\frac{V_L(t_1)}{T_L} - F_{A,N_2}(t_2)\frac{V_L(t_2)}{T_L}$$
$$= F_{S,N_2}(t_2)\frac{V_S(t_1)}{T_S}$$
$$V_L = \frac{T_L}{T_S}\left(\frac{F_{S,N_2}(t_2)V_S(t_2)}{F_{A,N_2}(t_1) - F_{A,N_2}(t_2)}\right)$$


In an N_2 washout experiment, the subject's cumulative expired volume into a
spirometer is 5 liters. Initially, the spirometer has a volume of 7 liters but contains no
N_2. At the end of the experiment, the molar fraction of N_2 in the spirometer is 0.026
and the F_{A,N_2} of the subject has decreased by 0.1. The final temperature of the
spirometer is 303K. What was the lung volume at which the subject was breathing?
$V_S(t_2) = 5 + 7 = 12$ liters. $F_{S,N_2} = 0.026$, $F_{A,N_2}(t_1) - F_{A,N_2}(t_2) = 0.1$, $T_S = 303$,
$T_L = 273 + 37 = 310$
$$V_L = \frac{310}{302}\left(\frac{0.026 \times 12}{0.1}\right) = 3.19 \text{ liters}$$

Helium-Dilution Estimate of Lung Volume
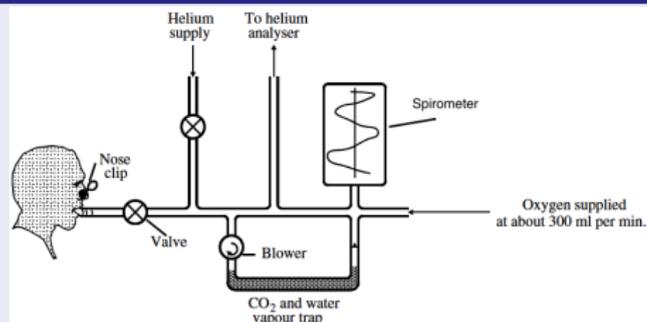
Helium is added to the system and the patient breathes several minutes so that Helium spreads into the lungs.

During this period oxygen is added at the rate which the lungs are absorbing the gas.

When $F_{A,He}(t_2) = F_{S,He}(t_2)$, the Helium analyzer will measure almost the same concentration. Assuming partial pressures in wet conditions, Mass-balance equation :
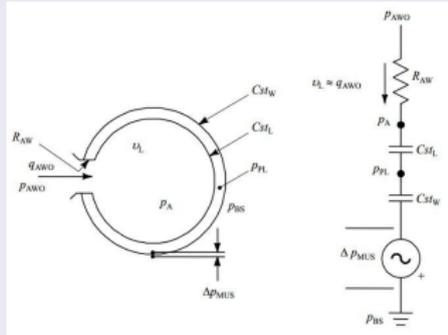
$$F_{S,He}(t_1)\frac{V_S(t_1)}{T_S(t_1)} = F_{S,He}(t_2)\frac{V_S(t_2)}{T_S(t_2)} + F_{A,He}(t_2)\frac{V_L(t_2)}{T_L(t_2)}$$

$$V_L = \frac{V_S(t_1)}{F_{S,He}(t_2)}\left(\frac{T_L}{T_S(t_1)}F_{S,He}(t_1) - \frac{T_L}{T_S(t_2)}F_{S,He}(t_2)\right)$$

Pulmonary Mechanics

Model for resting breathing
$y = Y - \hat{Y}$, Linearize around $\hat{Y}$

Pressure difference across the lungs : $\Delta P_L = (P_{AWO} - P_{PL}) - (\hat{P}_{AWO} - \hat{P}_{PL})$

$p_{AWO} - p_A = R_{AW} q_{AWO}, \quad p_A - p_{PL} = \frac{1}{C_{st_L}} v_L, \quad \Delta p_{MUS} + (p_{PL} - p_{BS}) = \frac{1}{C_{st_W}} v_L$

P_{AWO} : Pressure at the airway opening
P_A : Pressure within the lungs
ΔP_{MUS} : Average force on unit area on chest wall
P_{PL} : Average force on unit area of pleural surfaces
P_{BS}: Pressure on body surface
Q_{AWO} : Flow of gas at the airway opening
V_L : volume of gas in the lungs and airways

R_{AW} : Airway resistance
C_{st_w} : Chest-wall static compliance
C_{st_L} : Pulmonary static compliance

$R = \frac{\partial \Delta P}{\partial Q}, \quad C_{st} = \frac{\partial V}{\partial \Delta P}, \quad R_{AW} = \frac{\partial (P_{AWO} - P_A)}{\partial Q_{AWO}}, \quad C_{st_L} = \frac{V_L(t_2) - V_L(t_1)}{\Delta P_L(t_2) - \Delta P_L(t_1)}$
where $\Delta P_L = P_{AWO} - P_{PL}$

Pressure difference across the chest wall: $\Delta P_W = P_{PL} - P_{BS}$

Chest wall static compliance :

$C_{st_W} = \frac{V_L(t_4) - V_L(t_3)}{\Delta P_W(t_4) - \Delta P_W(t_3)}$

t_3 and t_4 are two instants at which system is static and muscles are relaxed.

For normal tidal breathing,

$P_{AWO} - P_{PL} = \frac{1}{C_{st_L}} v_L + R_{AW} \dot{v}_L$

Example

Design a volume controlled positive pressure ventilator that produces a constant (rectangular wave) flow ($\dot{v}_L = \dot{V}_L$) at the airway opening during inspiration of duration T_I until a set tidal volume is achieved. Then it can maintain that V_T for a set hold time, T_H before permitting a passive, unimpeded exhalation over the exhalation interval, T_E. Assuming the patient is sedated and paralyzed and has normal lungs, write an expression for

    i) peak inspiratory pressure that must be produced by the ventilator at the airway opening to achieve V_T and

    ii) the inspiratory pressure difference that the ventilator must maintain to hold the lung volume at V_T during V_H.

Solution

i)

$$p_{AWO} - p_{BS} + \Delta p_{MUS} = (\frac{1}{C_{st_W}} + \frac{1}{C_{st_L}})v_L + R_{AW}\dot{v}_L = \frac{1}{C_{st_{TR}}}v_L + R_{AW}\dot{v}_L$$

where $C_{st_{TR}} = C_{st_L}C_{st_W}/(C_{st_L} + C_{st_W})$

A PPV produces inspiration by incresing the pressure (p_{VENT}) at the airway opening instead of reducing the pressure on body surface.

For a paralyzed patient, $\Delta P_{MUS} = 0$. When the subject is exposed to atmospheric pressure, $P_{ATM} >>$ pressure changes on body surface.

Volume change is a ramp $v_L = \dot{V}_L t$ that reaches a maximum when $V_L = V_T$ at T_I.

Therefore, $P_{VENT} = \frac{1}{C_{st_{TR}}}v_L + R_{AW}\dot{v}_L$

and peak inspiratory pressure $= (\frac{1}{C_{st_{TR}}} + \frac{R_{AW}}{T_I})V_T$

ii)

During the inspiratory breath hold, flow is zero, and $v_L = V_T$.

Therefore, $p_{VENT} = \frac{V_T}{C_{st_{TR}}}$