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Review: Artifical Ventilation with Positive End-Expiratory Pressure (PEEP)

Historical Background, Terminology and Patho-Physiology

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Abstract. CPPV (continuous positive pressure ventilation) is obviously superior to IPPV (intermittent positive pressure ventilation) for the treatment of patients with acute respiratory insufficiency (ARI) and results within a few minutes in a considerable increase in the oxygen transport.

The principle is to add a positive end-expiratory plateau (PEEP) to IPPV, with a subsequent increase in FRC (functional residual capacity) resulting in re-opening in first and foremost the declive alveolae, which can then once again take part in the gas exchange and possibly re-commence the disrupted surfactant production. In this manner the ventilation/perfusion ratio in the diseased lungs is normalized and the intrapulmonary shunting of venous blood ($\dot{Q}_s/\dot{Q}_t$) will decrease. At the same time the dead space ventilation fraction (V_D/V_T) normalizes and the compliance of the lungs (C_L) increases.

The PEEP value, which results in a maximum oxygen transport, and the lowest dead space fraction, also appears to result in the greatest total static compliance (C_T) and the greatest increase in mixed venous oxygen tension ($P\bar{v}o_2$); this value can be termed "optimal PEEP".

The greater the FRC is, with an airway pressure = atmospheric pressure, the lower the PEEP value required in order to obtain maximum oxygen transport.

If the optimal PEEP value is exceeded the oxygen transport will fall because of a falling $\dot{Q}_t$ (cardiac output) due to a reduction in venous return. C_T and $P\bar{v}O_2$ will fall and V_D/V_T will increase. Increasing hyperinflation of the alveolae will result in a rising danger of alveolar rupture.

The critical use of CPPV treatment means that the lungs may be safeguarded against high oxygen percents.

The mortality of newborn infants with RDS (respiratory distress syndrome) has fallen considerably after the general introduction of CPPV and CPAP (continuous positive airway pressures). The same appears to be the case with adults suffering from ARI (acute respiratory insufficiency).

Abbreviations and Explanations

$(A\text{-}a)DO_2$	= Alveolo – arterial – O_2 – difference
ARI	= Acute respiratory insufficiency
CaO_2	= Arterial O_2-content
$\frac{CaO_2 - C\bar{v}O_2}{CaO_2}$	= O_2-extraction ratio
$(CaO_2 - C\bar{v}O_2) \times \dot{Q}_t = \dot{V}O_2$	= O_2-uptake, consumption
CC	= Closing capacity
CV	= Closing volume
CPAP	= Continuous positive airway pressure
CPPV (IPPV + PEEP)	= Continuous positive pressure ventilation
C_L	= Lung compliance
C_T	= "Total static compliance"
$C\bar{v}O_2$	= Mixed venous O_2-content ("O_2-reserve")
ETP	= End Tidal point
ERV	= Expiratory reserve volume
FRC	= Functional residual capacity
IC	= Inspiratory capacity
IPPV	= Intermittent positive pressure ventilation
IRV	= Inspiratory reserve volume

MABP	= Mean arterial blood pressure
MAP	= Mean airway pressure
$PaCO_2$	= Arterial CO_2-tension
PaO_2	= Arterial O_2-tension
PEEP	= Positive end-expiratory pressure
$P\bar{v}O_2$	= Mixed venous O_2-tension
PVR	= Pulmonary vascular resistance
$\dot{Q}_s/\dot{Q}_t$	= "Wasted perfusion", lung shunt in fraction of $\dot{Q}_t$
$\dot{Q}_t$	= Cardiac output
R_{AW}	= Airway resistance
RDS	= Respiratory distress syndrome
RV	= Residual volume
TLC	= Total lung capacity
$\dot{V}_E$	= Alveolar ventilation
V_D	= Physiologic dead space
V_D/V_T	= "Wasted ventilation", dead space ventilation in fraction of tidal volume
V_T	= Tidal volume
Heart work (W)	= $\dot{Q}_t$ x MABP
ZEEP	= Zero (ambient) end expiratory pressure.

Introduction

Continuous positive pressure ventilation (CPPV) and continuous positive airway pressures (CPAP) have been used for the treatment of both children and adults with respiratory distress (2, 9, 15, 18, 24, 30, 33, 37, 40, 41, 47). A decrease in the total mortality, from approx. 60 to 50%, has been demonstrated in newborn infants with respiratory distress syndrome (RDS). This is particularly evident in the weight group 1500–2000 grams, the latter reduction being from approx. 70 to 50% (9, 16, 30). After the introduction of PEEP (CPPV) for the treatment of acute respiratory insufficiency (ARI) the reduction in pulmonary mortality may be dramatic; from approx. 50 to 5% by means of optimal PEEP values (4,32).

As there appears to be some doubts about the mode of action insofar as its effects on humans are concerned, the object of the present survey is to give, on the basis of a literature study, a summary of the effects of CPPV especially on the lungs and on the oxygen supply of the organism.

History and Terminology

The expression "continuous positive pressure breathing" (CPPB) was first used by Barach (1938), who employed the principle in the treatment of patients with lung oedema during spontaneous respiration (3).

Early in the nineteen-forties, CPPB was studied in aviation medicine to ascertain whether or not it was possible to increase the partial pressure of oxygen in the alveolae during stratospheric flying. On account of the reduced venous return and $\dot{Q}_t$, and the discomforts these caused the pilot, intermittent positive pressure breathing (IPPB) was introduced instead (47). In order to increase the tolerance of jet-pilots for positive acceleration, CPPB is now being re-introduced, as well as other measures, among which is the anti-G suit (46).

In the middle of the nineteen-sixties, Jørgensen and his co-workers (28), introduced CPPV as a means of depressing $\dot{Q}_t$ for hypotensive anaesthesia. The term was also used by Pontoppidan's group (33) for controlled ventilation. Others described the same principle as intermittent positive positive ventilation (IPPPV) (37), and maintained airway positive pressures (MAPP) (11).

The positive pressure in the final phase of expiration has been termed positive expiratory pressure plateau (PEPP) (37). Thereafter, the term PEEP (positive end-expiratory pressure) was introduced by Ashbaugh & Petty (2). This appears to be the term most commonly used to-day. The term zero (ambient) end-expiratory pressure (ZEEP) is used by, among others, Rehder & coworkers (45).

Continuous positive airway pressures (CPAP) was introduced into paediatric practice by Gregory (18).

Definition of IPPV, PEEP, CPPV and CPAP

The term intermittent positive pressure ventilation (IPPV) is used for artificial ventilation with positive pressure during inspiration. The expiration is characterized by the pressure falling to atmospheric level (Fig. 1 A). The expression PEEP is employed for an increased pressure in the airways in relation to the atmospheric level after expiration is complete. PEEP is obtained by the expiration initially taking place in a passive manner, as during IPPV, after which further expiration is stopped by a pressure controlled valve, at a predetermined pressure level or by leading the expired air through a tube discharging it under water. PEEP can also be obtained by partial obstruction of the expiration (expiratory retard), providing the inspiration is commenced before the pressure in the airways falls to atmospheric level (2, 7, 10, 15, 24, 33, 37, 47) (Fig. 1 B, C, E and F).

CPPV consists of IPPV + PEEP and is characterized by the fact that the pressure in the airways never falls to atmospheric level.

In the majority of CPAP systems (5, 7, 9, 18, 21) expiratory retard and spontaneous ventilation are employed, during which, the airway pressure towards the end of the expiratory phases, has not reached atmospheric level. This can cause a reduced respiratory frequency and tidal volume (V_T) (6, 18, 36) with a reduction in alveolar ventilation ($\dot{V}_E$) and may cause CO_2 retention. The application of PEEP to a pressure cycled respirator, can also bring about a reduced V_T and CO_2 accumulation, providing the inspiratory pressure is not increased correspondingly (Fig. 1 B).

From the above it will be seen CPPB and CPAP are synonymous, the same applies to PEPP and PEEP.

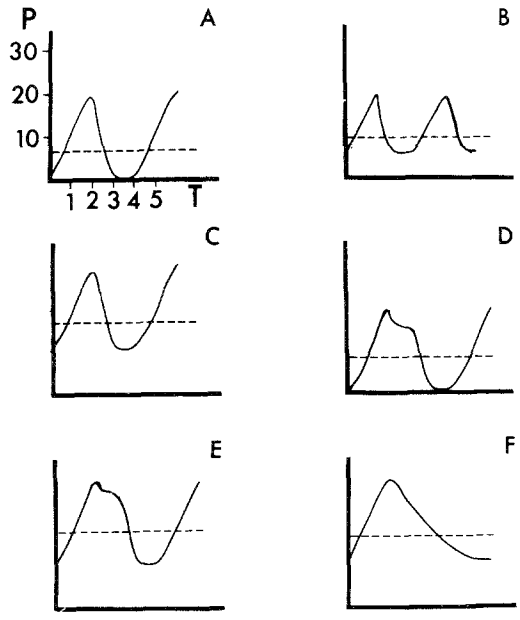

Fig. 1.
A. Pressure curve during IPPV, inspiration : exspiration = 1 : 1; B. CPPV with PEEP = 5 cm H_2O. Same inflation pressure as with A resulting in a lower V_T; C. CPPV with PEEP = 10 cm H_2O. Increased inflation pressure gives the same V_T as with A; D. IPPV + "inflation hold"; E. CPPV + "inflation hold"; F. "Expiratory retard" resulting in CPPV with a PEEP of 10 cm H_2O

MAPP, IPPPV and CPPV are used to describe artificial ventilation with IPPV + PEEP. All these ventilation principles with the exception of IPPV, have a common feature, which is, that they increase the volume of the lungs at rest (functional residual capacity = FRC) (Fig. 2).

The Importance of the Relationship between Functional Residual Capacity and Closing Capacity (FRC/CC)

During expiration from total lung capacity (TCL) to residual volume (RV) the airways of the lungs decrease in size (Fig. 2). This phenomenon is most pronounced in the dependent sections owing to the weight of the lungs themselves and the subsequent declive falling transpulmonary pressure with increasing intrapleural pressure. In the case of volumes near RV, the pleural pressure rises above the intraluminal airway pressure at the base of the lungs. This causes regional closure of the smaller airways ("airway closure"); those having a diameter of less than approx. 2 mm ("small airways"). The air is retained in the closed alveolar sections ("air-trapping") and will then reach a steady state with the venous blood. This results in venous admixture with arterial blood, in which case the shunt fraction ($\dot{Q}_s/\dot{Q}_t$) rises (1, 13, 14, 25, 39). The volume which is present in the lungs at the beginning of airway closure is called closing capacity (CC) (25) and, in young, healthy individuals, lies between RV and FRC

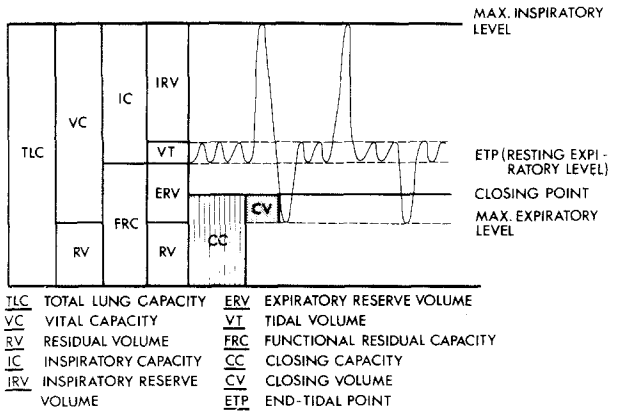

Fig. 2. Lung volumes in normal man

(25, 39). FRC is used to denote the volume which remains in the lungs after a normal expiration of V_T, or in other words, when the rest position of the lungs is reached at "end-tidal point" (ETP) (1).

In cases with an increased CC and/or reduced FRC (FRC/CC ratio < 1) airway closure occurs instead within V_T or within the inspiratory reserve volume (IRV) range, the result is an increased pulmonary shunting of the blood and as a result, arterial hypoxaemia (1, 14, 25, 39).

Some conditions under which the FRC/CC ratio < 1 may occur are given below:

a) FRC falls significantly during anaesthesia (1, 14). The cause of this appears to be a rise in the "retractive forces" of the lungs with a falling compliance of the lung parenchymia (C_L) and a rising compliance of the thoracic wall. This results in "low lung volume breathing" with reduced FRC values (53). The fall in arterial oxygen tension (PaO_2) together with the rise in carbon dioxide tension ($PaCO_2$) per- and post-operatively, are correlated to the FRC/CC ratio and with this to the magnitude of airway-trapping and airway closure (1, 12, 14, 25, 45, 52).

b) Peroperative reduction in FRC is also brought about by a fall in RV and expiratory reserve volume (ERV) during intraabdominal and -thoracic surgical procedures (1).

c) Postoperatively; spasms in the abdominal wall muscles will increase the intrapleural pressure and reduce FRC and thus may cause premature closure of the small airways (1). Opiates and sedatives administered postoperatively can bring about increase in intrapulmonary shunting (25). The mechanism is presumably the same as in a.

d) FRC will fall with a change from the standing to the supine position (13).

e) FRC is reduced with obesity (25).

f) Loss of "elastic recoil" in the elderly and undeveloped elastic recoil in small children, gives a high CC in relation to FRC (25).

g) The same occurs with an increase in pulmonary blood volume or lung fluid following cardiac congestion, liver cirrhosis, and during rapid intravenous infusions (25, 39).

h) With ARI (see below), FRC is severely reduced and falls far below the usual CC. The constantly closed alveolae can only be opened by means of "deep breaths" or by increasing FRC, for example by the use of IPPV + PEEP (CPPV) (23, 41). The above mentioned conditions may predispose to hypoxia during strain.

Definition of Acute Respiratory Insufficiency (ARI)

ARI can occur on account of alterations in lung function brought about by virus, fungal or bacterial infections; or it can occur after the inhalation of steam or smoke, after aspiration of sea and fresh water or stomach contents, and can also occur as a result of shock, blood transfusions, thoracic trauma, extracorporeal circulation or disseminated intravascular coagulation. Despite this multiple etiology, a pathophysiological pattern occurs consisting of: 1) hypoxaemia, 2) abnormally large intrapulmonary shunting of the venous blood and 3) the necessity for mechanical ventilation; which permits us to generalize and decide when acute respiratory insufficiency is present (4), termed here ARI.

With ARI, an increase in extravascular pulmonary fluid occurs, together with oedema either because of vascular congestion or destruction of the capillary endothelium, followed by exsudation of plasma into the interstitial spaces and alveolae, resulting in closure of airway sections in which surfactant production will cease. This condition causes a fall in FRC and C_L and increasing "mismatching" of ventilation and perfusion, resulting in increased dead space ventilation (V_D/V_T) and intrapulmonary shunt ($\dot{Q}_s/\dot{Q}_t$) with hypoxaemia (41).

The Pathophysiological Effect of CPPV (IPPV + PEEP) During ARI

a) FRC/CC

The use of a high V_T during IPPV can result in "airway opening" (52) and this can cause an increase in FRC and PaO_2 (8) despite a lower minute ventilation ($\dot{V}_E$) (38). However, IPPV will not be able to prevent airway closure as the pressure in the airways after the finish of the expiration will fall to atmospheric level (47). Great alveolar excursions is present result in the danger of alveolar and perivascular oedema. PEEP appears, despite a mean pressure of approx. the same magnitude as during IPPV to prevent these changes (41, 51). PEEP will be able to keep open a greater number of airways during the respiratory cycle (11, 40) and therefore a regeneration of surfactant in the re-opened surfactant-depleted alveolae appears possible (6, 41). It will be logical therefore to apply PEEP to IPPV (CPPV), in cases where there is a reduced C_L and FRC resulting in hypoxemia.

FRC rises, depending on C_L, almost linearly with increasing mean airway pressure (MAP) in both patients, and experimental animals with ARI, and the rise in PaO_2 is correlated to this (1, 2, 3, 13, 14, 40, 47). At the same time the expiratory reserve volume (ERV) rises, while the inspiratory capacity (IC) falls. CC increases, presumably owing to a rise in RV, but not nearly as much as FRC. The vital capacity (VC) remains almost unchanged (47). The lower FRC is with ZEEP, the higher PEEP values must be used, in order to obtain optimal oxygenation conditions (48).

b) V_D/V_T–PCO_2

In the sitting position the greater part of V_T is distributed to the relatively overperfused areas, presumably due to intrapulmonary reflexes (29). With a FRC/CC ratio < 1 with airway closure within the V_T range, the ventilation of the lower section will be reduced or cease, and V_T will be distributed to the apical, relatively under-perfused sections. This will result in an increased V_D/V_T ratio and may give CO_2 retention (41): In most cases patients with ARI have an increased $PaCO_2$ with an increased V_D/V_T ratio.

However, this abnormal V_D/V_T ratio is normalized under optimal CPPV treatment, owing to an increase in FRC with airway opening and a redistribution of V_T to the dependent sections. As a result of this, the ventilation/perfusion ratio normalizes (2, 15, 17, 33, 37, 40, 47).

Suter and his co-workers (48) have demonstrated that in patients with ARI, the abnormal V_D/V_T falls during CPPV with increasing PEEP-values until a certain optimal PEEP value has been reached. Should PEEP be further increased then rising "dead-space ventilation" is again observed. At the same time, after a certain rise, the total static compliance (C_T) falls again, suggesting a hyperdistension of the alveolae. Together with the rising "dead-space ventilation" and the falling C_T a fall in $\dot{Q}_t$ was also seen, which per se, can cause an increased V_D/V_T ratio.

Hyperdistension of the alveolae can also occur with regression of the pathological lung condition during constant PEEP values (41). Unnecessary high pressure should be avoided before an "all over" hyperinflation-effect of the alveolae occurs, with its increasing danger of alveolae rupture (48): i.e. before V_D/V_T begins to rise after an initial fall.

Before this general hyperinflation effect is observed, however, some individual alveolae may be hyperdistended with a subsequent danger of rupture.

In patients with chronic left sided heart failure or with mitral valve disease, the perfusion of the basal lung sections may be reduced owing to morphological changes in the blood vessels in these areas. The apical sections will be correspondingly better perfused (26). With a redistribution of V_T to declive sections during treatment with PEEP, the V_D/V_T ratio may rise in these

patients resulting in CO_2 retention which in turn may require a greater minute ventilation (49).

From the above reasons it follows that the CO_2 tension of arterial blood ($PaCO_2$) and the minute ventilation should be closely observed after a change over from IPPV to CPPV, or with increasing PEEP values, or with a shift from IPPB to CPAP (see also page 3).

c) $\dot{Q}_s/\dot{Q}_t$–PaO_2

After a few hours, ventilation with an oxygen fraction (FIO_2) in the inspiratory air $\geqq 0.8$, results in a continuous rise in intrapulmonary shunt fraction of cardiac output ($\dot{Q}_s/\dot{Q}_t$), which, after some time, will result in anoxia and cause death (42, 47). The causes of this are structural, pathological changes in the lung which also occurs, but more slowly, with FIO_2 values above 0.5. FIO_2 values of up to a maximum of 0.4 appear to be safe (42). In the majority of patients with ARI, it is possible, by adding PEEP to IPPV or spontaneous respiration, to maintain acceptable oxygenation without the use of inacceptable FIO_2 and V_T values (2, 15, 16, 18, 30, 32, 33, 36, 37, 40, 41, 47).

As a rule, CPPV in patients with ARI will result in a considerable increase in PaO_2. This increase is correlated to the rise in FRC (and with this the ratio FRC/CC), and to the degree of airway opening (25). $\dot{Q}_s/\dot{Q}_t$ ratio and the alveolo-arterial oxygen difference (A-a DO_2) falls. C_L rises and is correlated to the rise in PaO_2, but despite an additional, even though slower, rise in PaO_2 it falls again with greater than optimal values. The same applies to C_T which can be estimated comparatively easily (see below) (48). The effect on PaO_2 is most convincing in patients with alveolar collapse and airway closure resulting in a reduced C_L and FRC/CC ratio, with an increase in shunting of the blood in the lungs (2, 13, 15, 17, 24, 33, 37, 40, 47, 48).

After the addition of PEEP to IPPV in patients with ARI, the PaO_2 is immediately increased and reaches a maximum after approximately 12–25 minutes. After this, the PaO_2 usually rises slowly for the next 12–48 hours during regression of the pathological state of the lungs, so that FIO_2 and thereafter PEEP may be reduced. If PEEP is suddenly discontinued, PaO_2 falls within a few minutes (15, 47).

It must be concluded from the above that CPPV appears superior to IPPV, even with the same mean airway pressure (MAP).

This seems to be confirmed by Cheney's work (8, 36) in which CPPV was found to be more effective than IPPV with regard to reduction in the shunt ($\dot{Q}_s/\dot{Q}_t$) during experimental lung oedema in dogs.

It was found that:

1) a given reduction in the intrapulmonary shunt required a doubling of PEEP (5–10 cm H_2O), but five times the V_T (5–25 ml/kg) was required with IPPV.

2) with a transition from IPPV with V_T = 15 ml/kg, the shunt could be reduced from 44% to approximately 26% by means of 10 cm PEEP, despite V_T being reduced to 5 ml/kg.

3) above a certain MAP value, no additional reduction was found in the intrapulmonary shunt, presumably because that the FRC/CC ratio had become > 1.

Falke and his co-workers (15) found that patients with mainly unilateral changes developed an additional increase in PaO_2 under CPPV, if the patient lay with the healthy lung downwards. This can be explained by a reduction in the shunt-perfusion in the upper lung, where the tendency to airway closure was greatest. In agreement with this Rehder (45) found that normal anaesthesized persons lying on their side had a reduction in perfusion in the upper lung. Kaneko et al. (29) were also able to demonstrate that the ventilation/perfusion ratio ($\dot{V}/\dot{Q}$) in normal man was least in the dependent and greatest in the upper sections. In addition it is stated that a reduced tendency to formation of atelectasia and airway closure in the dependent areas resulting in a rise in PaO_2, is present with frequent changes in position (17, 41).

Colgan and co-workers (10) found that a "low-output state" after heart surgery, does not necessarily contraindicate the use of CPPV. Intrapulmonary shunting, when elevated under IPPV, could be reduced under CPPV and a continuous increase of PaO_2 generally followed increasing PEEP values, even in cases where a slight fall in cardiac output occurred.

Trichet and co-workers (49) were able to demonstrate the same phenomena in patients after aortic valve replacement. On the other hand, patients with increased pulmonary vascular resistance (PVR) as those with chronic congestive heart failure, showed, after mitral valve replacement, minimal influence of CPPV on the shunt fraction and oxygenation. IPPV, with lower MAP, appears preferable in these cases, in order to avoid intensification of ventilation-perfusion inequality.

d) The Effect on the Circulation and on the O_2-Transport

The cardiac output ($\dot{Q}_t$) may be reduced following a reduction in the venous return to the heart and/or fall in the pump activity of the heart (19). The oxygen transport to the periphery of the body ($CaO_2 \times \dot{Q}_t$) will, with an unchanged oxygen content of arterial blood (CaO_2), decrease. The tissues will, with a constant oxygen consumption ($\dot{V}O_2$), offset this decrease by a greater extraction of oxygen per volume unit blood. It follows that the oxygen content in the venous blood ($C\bar{v}O_2$) falls. This can best be evaluated from mixed venous blood from the pulmonary artery (10, 19, 28, 31, 48) (see Fick's principle).

The heart's work ($W = Q_t \times$ MABP (mean arterial blood pressure)) will decrease during a fall in $\dot{Q}_t$ and the circulating blood volume will be redistributed to the vital organs (19). Despite a slight to moderate fall in $\dot{Q}_t$ it is possible

to increase the oxygen transport by means of CPPV, for, via its favourable effect on the intrapulmonary shunt in diseased lungs, it should induce a relatively strong increase in CaO_2. This will result in the relationship between the heart's work and the oxygen available to the myocardium ("cardial economy") being improved, providing, of course, that the perfusion of the coronary vessels is not compromised. The oxygen transport to the other vital organs will be permitted to rise, thus enabling the function of these to be maintained or improved.

The factor which will have an immediate influence on $\dot{Q}_t$ under artificial ventilation, will be the increased intrathoracic pressures transmitted to the heart, great vessels, lung capillaries and lymphatic vessels; resulting in cardial compression and reduced venous blood and lymph return, and with this, a reduction in filling pressures in both the right and left sides of the heart (19, 34, 43, 49).

In a diseased lung with a reduced compliance (C_L) and high airway resistance (R_{AW}), this transmission will be less than in normal lungs, inasmuch as a "steady state pressure" as PEEP is reduced by the abnormally increased "retractile forces". The transmission of the inflation pressure will also be reduced to a certain but a slight extent, owing to an increased R_{AW} (15, 17, 24, 41, 47). In a two investigations into the influence of CPPV on $\dot{Q}_t$ during the use of conventional PEEP values (5–20 cm H_2O) in patients with ARI, it is possible to see that the oesophageal pressure in the majority of cases hovered around 0 cm H_2O and at the most 10–20% of MAP, and did not bring about a measurable reduction in $\dot{Q}_t$ (24, 33). In several other studies concerning ARI the O_2-transport ($CaO_2 \times \dot{Q}_t$) is reported to be drastically increased (2, 8, 10, 15, 37, 47). There is, however, great variation from patient to patient, in all probability depending on the individual FRC/CC ratios, circulating blood volume, cardiac function and different compensation responses to decreased venous return.

Suter and co-workers (48) were able to demonstrate that up to a certain point increasing PEEP values in patients with ARI resulted in increasing oxygen transport due to a rise in CaO_2, while $\dot{Q}_t$ remained more or less constant. Until this point was reached, a rise in oxygen tension in mixed venous blood ($P\bar{v}O_2$), a fall in V_D/V_T and a rise in C_T towards normal values, was seen. After this, owing to a fall in $\dot{Q}_t$, the oxygen transport fell with an additional increase in PEEP, despite the fact that PaO_2 continued to show a tendency to rise. At the same time, the $P\bar{v}O_2$, V_D/V_T and C_T deteriorated again. The optimal PEEP value corresponding to maximum oxygen transport were found to vary from patient to patient as would be expected from the different pathological states, and were dependent on the initial values of FRC. The lower FRC at ZEEP, the higher the PEEP values required. C_T was estimated as the arithmic mean of PEEP and the obtained inspiratory pressure, divided into V_T. Using the C_T values as an indicator of "optimal PEEP" the authors concluded that this was an easy and safe method of determining the individual optimal PEEP value. Optimal, high level PEEP values of up to 57 cm H_2O have been used with good results by others in conjunction with intermittent mandatory ventilation, i.e. during spontaneous respiration with supporting low frequency respirator ventilation (32).

Quist and co-workers (43) could show, that in dogs under halothane anesthesia, PEEP – provided transmission of MAP to the heart and great vessels – resulted in a reduction of the transmural filling pressure with subsequent fall of $\dot{Q}_t$. These changes could, however, by means of transfusions, be returned towards normal values along a Starling curve. The urine production which was reduced following the fall in $\dot{Q}_t$, rose again. Therefore it may appear that a hypovolemic condition was imitated via the increased MAP. However, in more or less awake patients, a positive ino- and chronotropic compensatory response with vasoconstriction may retain $\dot{Q}_t$ at initial levels despite slight reduction of filling pressures.

If the heart works along the horizontal part of its function curve, then an increased venous return, for example caused by a reduction in airway pressure – as it may occur during weaning from respirators or during reduction of PEEP – results in increased preload leading to cardiac dilatation with paradoxical fall in $\dot{Q}_t$ and increasing pulmonary stasis and oedema. It is therefore not surprising that institution of artificial ventilation, i.e. an increase of MAP – eventually by means of PEEP – can result in the opposite taking place, namely a rise in $\dot{Q}_t$ and a reduction in pulmonary stasis on the basis of lowering left-sided filling pressure (43, 49).

Patients with ARI will, as a rule, have a high $\dot{Q}_t$ owing to shunts and hypoxaemia, with a resulting increased heart work ($\dot{Q}_t \times$ MABP) and a reduction in the oxygen available to the myocardium and to the body as a whole (10, 47).

Providing the shunt and hypoxia can be reduced, by means of artificial ventilation, eventually with CPPV, the given fall in $\dot{Q}_t$ accompanied by a strong increase in CaO_2 will be a great advantage to the patients, with improved cardiac "economy" and increased available oxygen to both the heart and periphery, providing the perfusion pressure gradient does not decrease too much. In addition to this, an advantageous reduction in oxygen consumption will occur with sedation and the taking over of the respiratory work, and may result in additional, advantageous reduction in $\dot{Q}_t$ and thus heart work (41, 47). However, care should be taken to avoid hypoperfusion of vital organs, especially, the heart and brain.

In patients with healthy lungs the Q_t is rapidly influenced by CPPV, particularly following drug blockade of the compensatory mechanisms (see below), in hypovolemia and with cardiac insufficiency. The O_2 transport can thus be rapidly reduced (28, 34) as there is hardly any possibility of increasing the CaO_2 to any great extent in these patients who usually have a maximum saturation of the arterial blood (see dissociation curve of the oxyhaemoglobin).

According to the above, it is easy to understand the rather confusing effects of CPPV on $\dot{Q}_t$ reported in the literature, ranging from a slight increase to moderate fall and why a depression already present of the $\dot{Q}_t$ is enhanced with increasing PEEP values, during which a fall in the peripheral O_2 availability can be observed (see 2, 8, 10, 15, 32, 33, 35, 36, 37, 40, 47, 48). The optimal PEEP values as estimated by Suter and co-workers (48) should therefore not, in all probability, be exceeded to any great extent.

Various compensatory mechanisms will come into play with a reduction of $\dot{Q}_t$. The object of these is to optimise the discrepancy between circulating blood volume, cardiac pump activity and the oxygen requirements of the organism:

1) Oxygen extraction rises, $C\bar{v}O_2$ and $P\bar{v}O_2$ fall (10, 28, 31, 48).

2) The sympatic tone is increased via the baro and chemo receptors resulting in a peripheral vasoconstriction and increased cardiac chrono and inotropy (19, 44), providing sympatic blockade is not present.

3) The circulating blood volume is redistributed to the vital organs having the higher oxygen consumption (19, 44).

4) Urine production becomes reduced become of a decrease in filtration pressure and redistribution of the intrarenal perfusion (20, 22).

5) Salt and water retention occurs together with an additional blood vessel constriction via neural and hormonal mechanism (ADH, ACTH, Aldosterone-Renin-Angiotensin) (20, 22, 41).

These effects of the alteration in the haemodynamics following a depression of $\dot{Q}_t$ can be measured and may together with other parameters be used for monitoring during treatment with CPPV.

Monitoring During CPPV-Treatment

PvO_2

as an expression of the bodies O_2 reserve is probably the one single parameter that gives most information on the ability of the cardiopulmonary mechanisms to cover the oxygen requirements. A $P\bar{v}O_2$ of less than 25 mm Hg must be assumed to be inacceptable (10).

If the $P\bar{v}O_2$ falls after an initial rise during increasing PEEP, then the airway pressure should not be further increased but maintained at a level where a maximum $P\bar{v}O_2$ is present, inasmuch as this correlates with a maximum oxygen transport (32, 48). This, however, may rise further by increasing circulating blood volume (43) or by means of catecholamine stimulation (10).

C_T

estimated by dividing the tidal volume by the difference between the end inspiratory plateau and PEEP (48), increases during rising PEEP values until it, after a certain maximum again falls. The maximum C_T correlates to the greatest possible oxygen transport, and V_D/V_T also has its lowest value at this point.

PaO_2

Analysis of this factor will allow the exclusion of arterial hypoxia, and *$PaCO_2$* determinations reveal hypo- or hyperventilation. Analyses of acid-base relationship and eventually determination of the pyruvate/lactate-ratio may reveal peripheral hypoxia and hypoperfusion.

Monitoring the *peripheral skin (toe-) temperature* and the *urinary production per hour* will, ceteris paribus, reveal reduction in $\dot{Q}_t$ and kidney perfusion. This may, however be reversed by increasing the circulating blood volume or by catecholamine stimulation eventually in combination with vasodilation, which by means of an increase of $\dot{Q}_t$ may result in a rising O_2 transport with subsequent rising $P\bar{v}O_2$ (10, 31).

The *pressure changes in the great veins and the oesophagus* will reflect the transmission of the airway pressure to the heart and the great vessels. An impression of the right ventricle's transmural filling pressure can be obtained by subtracting the oesophageal pressure from the central venous pressure (CVP) (43). If this falls, then $\dot{Q}_t$ and MABP may fall too, (see Starling's heart law) with a reduction in the O_2 transport as a result, providing compensatory response or a rise in CaO_2 does not compensate for this.

According to the above it will rarely be necessary to monitor $\dot{Q}_t$ or left sided filling pressures during CPPV therapy, unless a concurrent heart disease indicates this necessity.

Measurement of blood pressure and observation of capillary response, venous filling and skin colour together with other clinical conditions shall of course, also be carried out.

Indications for Treatment with CPPV in ARI

The majority of authors appears to agree that hypoxaemia ($PaO_2 < 70$ mm Hg) during IPPV with $FIO_2 = 0.5$ and a high tidal volume and indications of ARI with a reduced C_L and FRC are indications for the commencement of CPPV, which also can be employed in the treatment of atelectasis (2, 9, 15, 17, 18, 32, 33, 37, 40, 41, 47).

The use of IPPV or CPPV can be of considerable advantage in cardiac failure owing to increased "preload" resulting in a reduction of venticular function as seen with cardiac lung oedema (43, 49).

Contraindications

1) Hypovolaemia may result in shock when MAP is increased (2, 47).

2) Patients with an already increased FRC – such as with chronic obstructive lung disease – will probably not benefit of CPPV (2, 47).

3) Neither will CPPV be of benefit in attacks of bronchial asthma; in such cases expiratory retard will probably be preferable owing to improved emptying of already hyperdistended alveolae (2, 4, 47).

4) In patients with an increased resistance in the pulmonary vessels, CPPV may cause deterioration in the ventilation/perfusion ratio (49).

5) Congenital lobular emphysema and already existing pneumothorax will theoretically worsen under the influence of continuous positive pressures.

6) A cardiac shunt might worsen or change in right-left direction. However, this does not appear to have been the object of any study.

7) Care seems especially to be necessary in cases of sympatic blockade brought about by drugs, decreased heart function, coronary insufficiency, valvular heart disease and vascular stenosis, because of the risk of an extreme fall in $\dot{Q}_t$ resulting in hypoperfusion of vital organs.

8) Patients who have healthy lungs will presumably have no real benefit from PEEP, in such cases IPPV will be sufficient when artificial ventilation is required (2, 47).

Side Effects and Complications

Unnecessary alveolar distention brought about by increasing FRC too much may cause:

1) Alveolar rupture and pressure pneumothorax, pneumomediastinum and pneumopericardium (2, 47).

2) With high PEEP values subcutaneous emphysema may occur, even without other complications (32). Under these circumstances it may be indicated to establish prophylactic pleural drainag.

3) Increased V_D/V_T ratio which may cause CO_2-retention (48).

4) Increased hydrostatic pressure on the venous and lymphatic side, which may result in peripheral oedema (43).

5) A reduction in flow in the portal vein, depending on $\dot{Q}_t$ (27).

It is not exactly known if IPPV resulting in considerable alveolar excursions will do more damage than CPPV with the same MAP or the same degree of oxygenation of the organism, but in animal experiments PEEP seems to protect from alveolar damage and surfactant inactivation brought about by high V_T during IPPV (41, 51).

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