 Scalars and loops in mechanical ventilation

29/3/2019
Scalars

- Scalars waveform representations of pressure, flow or volume on the y axis vs time on the x axis
- Ventilators measure airway pressure and airway flow
- Volume is derived from the flow measurement
- *Pressure and flow* provide all the information necessary to explain the physical interaction between ventilator and patient
- Volume scalar – tidal volume delivered during inspiration and expiration
Scalars
Flow time waveform

• Inspiratory arm
  • Active in nature
  • Character dependent on the ventilator flow settings and mode of ventilation
  • Volume A/C – ‘square wave’ ‘ramp pattern’
  • Pressure A/C – Decelerating ramp – subtle variation compliance and/or demand

• Expiratory arm
  • Passive
  • Character dependent on the elastic recoil and lung resistance
  • Patients active effort

Iyer et al. ATS review: Ventilator waveform interpretation and analysis
The ‘square wave’ flow pattern

The inspiratory flow rate remains constant over the entire inspiration.

The expiratory flow is passive and is determined by airways resistance and the elastic recoil of the lungs.

Inspiratory time = Tidal volume
Flow rate
The ‘decelerating ramp’ flow pattern

The inspiratory flow rate decelerates as a function of time to reach zero flow at end inspiration.

For a given tidal volume, the inspiratory time is higher in this type of flow pattern as compared to the square wave pattern.

Inspiratory time = Tidal volume / Flow rate
Flow time waveform

• Square wave
  • Inspiratory time shortest to achieve set $V_t$
  • Highest $P_{peak}$
  • Low mean pressure (Hemodynamic stability – CO and venous return unaffected)

• Decelerating ramp
  • Inspiratory time is longer to achieve similar $V_t$
  • Lower $P_{peak}$
  • $P_{mean}$ high can affect CO and venous return

• Ascending ramp
  • Gradual rise in flow associated with discomfort and flow hunger

• No studies flow pattern alone but animal models show no significant difference between square and decelerating ramp in terms of oxygenation, CO2 elimination or hemodynamic parameters

Markström AM et al. Anesthesiology. 1996 Apr;84(4):882-9
Pressure curve

• The pressure curve is positive during mechanical ventilation.
• Baseline pressure above zero appears when PEEP is applied and assisted inspiration is shown as an increase in pressure above PEEP during volume delivery.

Jean Michel Arnal Robert Chatburn; Monitoring Mechanical Ventilation Using Ventilator Waveforms; 1st ed; 2018; Springer
Pressure time waveform

• Ventilator circuit
• Generation of pressures within the circuit
• The equation of motion
• Pressure time waveform
The basic ventilator circuit diagram

Essentially the circuit diagram of a mechanically ventilated patient can be broken down into two parts:

1. The ventilator, which makes up the first part of the circuit. Its pump-like action is depicted simplistically as a piston that moves in a reciprocating fashion during the respiratory cycle.

2. The patient’s own respiratory system, which makes up the second part of the circuit. The diaphragm is also shown as a second piston, causing air to be drawn into the lungs during contraction.

These two systems are connected by an endotracheal tube, which we can consider as an extension of the patient’s airways.
Generation of airway pressures

• Respiratory system mechanical system consisting of a resistive (airways) and elastic (lungs and chest wall) element in series

• Pressure contributed by airways - result of inherent resistance of the airways and the rate of airflow (so Flow x Resistance)

• Contribution of pressure by elastic element depends on compliance of lung+chest wall and volume being given (so Volume/Compliance)

\[ P_{aw} = \text{Flow} \times \text{Resistance} + \frac{\text{Volume}}{\text{Compliance}} \]
Generation of airway pressures

Thus the equation of motion for the respiratory system is

\[ P_{\text{applied}}(t) = P_{\text{res}}(t) + P_{\text{el}}(t) \]

The total 'elastic' resistance \( (E_{\text{rs}}) \) offered by the respiratory system is equal to the sum of elastic resistances offered by the lungs \( (E_{\text{lungs}}) \) and the chest wall \( (E_{\text{chest wall}}) \). Thus to move air into the lungs at a given time \( (t) \), the ventilator has to generate a pressure \( (P_{\text{applied}}) \) that is sufficient to overcome the pressure generated by the elastic \( (P_{\text{el}}) \) and airway \( (P_{\text{aw}}) \) resistances offered by the respiratory system at that time.

Iyer et al. ATS review: Ventilator waveform interpretation and analysis
Pressure time waveform

• Reflection of pressures generated within airways during each phase of the ventilator cycle

1. Pressure generated to overcome airway resistance
   No volume delivered

2. Subsequently pressure rises linearly to reach peak
   Corresponds to flow and volume delivery

3. After pressure peaks and flow declines pressure drops by amt = Pres and reaches Plat

4. Return to baseline after pause/peak to set PEEP during expiration

Iyer et al. ATS review: Ventilator waveform interpretation and analysis
Pressure-time waveforms using a ‘square wave’ flow pattern

Normal values:
- $P_{\text{peak}} < 40 \text{ cm H}_2\text{O}$
- $P_{\text{plat}} < 30 \text{ cm H}_2\text{O}$
- $P_{\text{res}} < 10 \text{ cm H}_2\text{O}$

Normal pressure-time waveform
With normal peak pressures ($P_{\text{peak}}$),
plateau pressures ($P_{\text{plat}}$) and
airway resistance pressures ($P_{\text{res}}$)
Pressure-time waveform - obstruction

\[ P_{aw} = \text{Flow} \times \text{Resistance} + \text{Volume} + \text{PEEP} \]

Compliance

Increase in peak airway pressure driven by an increase in the airways resistance normal plateau pressure

Normal

e.g. ET tube blockage

Square wave flow pattern
ET Tube obstruction
Increase in the peak airway pressure driven entirely by an increase in the airways resistance pressure caused by excessive flow rates shortened inspiratory time and high flow.

\[ P_{aw} = \text{Flow} \times \text{Resistance} + \text{Volume} + \text{PEEP} \]

Compliance

Normal (low) flow rate

Square wave flow pattern

#3
e.g. high flow rates
High airflow causing increase in airway resistance
Increase in the peak airway pressure is driven entirely by the decrease in the lung compliance.

\[ P_{aw} = \text{Flow} \times \text{Resistance} + \text{Volume} + \frac{\text{PEEP}}{\text{Compliance}} \]
Reduced compliance
Pressure time waveform with decelerating ramp flow

- Normal: Pressure time waveform with normal PIP and normal Pplat.
- High Raw: COPD: Pressure time waveform with high PIP.
- High flow: (short Inspiratory time): Pressure time waveform with high PIP and normal Pplat.
- Low Compliance: ARDS: Pressure time waveform with high PIP and high Pplat.
Volume time waveform

- Volume is not measured directly
- Derived from the flow measurement - area under the flow-time curve
- Important info on airleak, active expiration and hyperinflation
Independent and dependent variables

• Pressure control - preset inspiratory pressure and time with volume and flow delivery dependent on the patient’s respiratory mechanics

• Pressure is independent variable, while volume and flow are dependent variables

• Volume control - right-hand side of the equation is predetermined (preset tidal volume and flow) making pressure delivery dependent on the patient’s respiratory mechanics

• Volume and flow are considered independent variables in the equation of motion, and pressure is the dependent variable
# Mode of ventilation and waveforms

<table>
<thead>
<tr>
<th>Mode of ventilation</th>
<th>Independent variables</th>
<th>Dependent variables</th>
<th>Waveforms that will be useful</th>
<th>Waveforms that normally remain unchanged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Control/ Assist-Control</td>
<td>Tidal volume, RR, Flow rate, PEEP, I/E ratio</td>
<td>$P_{aw}$</td>
<td>Pressure-time: $\rightarrow$ changes in $P_{ip}$, $P_{plat}$ Flow-time (expiratory): $\rightarrow$ changes in compliance Pressure-volume loop: $\rightarrow$ overdistension, optimal PEEP</td>
<td>Volume-time Flow time (inspiratory) Flow-volume loop</td>
</tr>
<tr>
<td>Pressure Control</td>
<td>$P_{aw}$, Inspiratory time (RR), PEEP and I/E ratio</td>
<td>$V_t$, flow</td>
<td>Volume-time and flow-time: $\rightarrow$ changes in $V_t$ and compliance Pressure-volume loop: $\rightarrow$ overdistension, optimal PEEP</td>
<td>Pressure-time</td>
</tr>
<tr>
<td>Pressure support/ CPAP</td>
<td>PS and PEEP</td>
<td>$V_t$ and RR, flow, I/E Ratio</td>
<td>Volume- time Flow-time (for $V_t$ and $V_E$)</td>
<td></td>
</tr>
</tbody>
</table>
Waveforms observed during Volume A/C

• Pressure time
  • Influenced by patients efforts compliance and resistance

• Flow time
  • Inspiratory flow pattern fixed
  • Expiratory flow – depends on compliance, elastic recoil pressure presence of active expiration and obstruction to flow

• Volume time
  •Leaks
  • Dynamic hyperinflation
Low compliance increase in elastic recoil with increased PEF
Stress index – Pressure time waveform

• At constant flow, the slope of the airway pressure-time curve is proportional to elastance (inversely proportional to resistance)

• In passively breathing patients and at constant flow – shape of the pressure time curve provide overview about compliance/recruitable/overdistension

• When rate of pressure increase with time is small indicating a recruitable lung (Curve convex upwards)

• When rate of pressure change is higher indicating overdistention
Stress index Pressure time waveform

- Stress index < 1: Increase PEEP (Recruitment)
- Stress index = 1: Ideal PEEP
- Stress index > 1: Decrease PEEP (Overdistension)
Stress index – Pressure time waveform

• The stress index is a dimensionless coefficient, can quantitatively describe the shape of the pressure time curve
  
• Paw = k × tb

• Paw is the airway pressure, t is the time, k is a constant of proportionality (to make time equal pressure), and b is a parameter that describes the degree of concavity of the pressure-time curve

• >1 overdistension <1 recruitable lung

• It requires dedicated data acquisition instruments and analytic software (ie separate module)

• Servo-i, Maquet, Solna, Sweden has a pre-installed software module
Stress index can be accurately determined by visual inspection

• 36 subjects and collected 220 SI assessments by visual inspection and software calculated values

• Agreement between visual SI classification by the first and the second observer and the reference standard substantial (weighted kappa {95% CI} being 0.86 {0.80 – 0.92} and 0.88 {0.82 – 0.94})

• Inter-observer reliability was high (weighted kappa {95% CI} 0.96 {0.92 – 0.99})

• Accuracy (95% CI) for visual SI classification was 93% (88 – 96%)
Stress index can be accurately determined by visual inspection.
Mean airway pressure

- Average pressure over a ventilatory cycle (one inspiration and one expiration)
- Area below the pressure-time curve divided by the ventilatory period (inspiratory time plus expiratory time)
- Numerically, calculated as the average of many pressure samples taken over the ventilatory period
- PaO2 is proportional to mean airway pressure
- Cardiac output may be inversely proportional
- Increase airway pressure or increases the I:E ratio (increasing inspiratory time or decreasing expiratory time) increases mean airway pressure
Mean airway pressure
Waveforms observed in pressure A/C

• Pressure time wave form - preset
  • Time/flow/pressure triggered
  • Pressure targeted
  • Time cycled

• Volume time wave form
  • Volume delivered depends on compliance, resistance and insp muscle usage

• Flow curve
  • Decelerating pattern
  • Rapid increase in flow initially followed by an exponential drop
  • Insp flow generated by the pressure gradient between the proximal airway and the alveoli
Waveform observed in pressure A/C
Shape of the flow curve in pressure A/C

• Variation with varied respiratory system mechanics

- Time constant = Product of compliance and resistance
  - Short time constant (Low compliance and/or resistance) = Rapid inflation and decline in pressure gradient
  - Long time constant (High compliance and/or resistance) = Slow inflation and decline
Shape of flow curve in pressure A/C

- Variation with inspiratory time
Waveforms observed in pressure support

- Flow or pressure triggered, pressure targeted and flow cycled
- Pressure curve may be shaped by a set rise time
- Flow curve characteristics determined by Inspiratory time constant (compliance, resistance) and patients effort
Waveforms observed in pressure support

- Pressure rise time
  - Pressure rise time is the time to increase pressure from PEEP to set pressure.
  - Short rise time = higher peak flow
  - Longer rise time = shorter peak flow
  - Duration of insufflation also affected as cycling is related to peak flow
Waveforms observed in pressure support

• Shape of inspiratory flow
• Deviation of inspiratory flow from the exponential declining pattern indicates a respiratory muscle effort (inspiratory or expiratory)
• Rounded or constant inspiratory flow - a significant inspiratory effort during insufflation indicates insufficient pressure support
• Change in slope of inspiratory flow toward the baseline suggests expiratory muscle contraction during insufflation - caused by excessive pressure support or prolonged mechanical insufflation (delayed cycling)
Waveforms observed in pressure support

- Decrease Inspiratory Pressure support
- Increase Expiratory Trigger Sensitivity
Waveforms observed in pressure support

- Early cycling
- Flow from ventilator ends but patient still making inspiratory effort
- Distortion of flow and pressure waveform at onset of expiration
- Abrupt initial reversal of expiratory flow toward zero, indicating patient's inspiratory effort is prolonged
- Exaggeration of same = autotrigger
Early cycling
Common problems that can be diagnosed by analysis of scalars

- Abnormal lung mechanics
  - Auto PEEP
  - Overdistension
- Asynchrony
  - Trigger
  - Cycle
  - Flow
- Circuit related
  - Leaks
  - Secretions
Overdistension

- Stress index upward concavity of the pressure time scalar
- Increased Ppeak and Pplat
- High peak expiratory flow
Auto PEEP

- Expiration is interrupted before its natural end by the next inspiration, some un-expired residual gas remains in thorax.
- Exerts a pressure onto the respiratory circuit.
- As a result, the alveolar pressure at the end of expiration is higher than zero (atmospheric pressure = 0).
- This incompletely emptying is called dynamic hyperinflation, and the positive alveolar pressure is called PEEP or auto PEEP.

**Physiologic mechanisms of auto-positive end-expiratory pressure**

- Dynamic hyperinflation
- plus intrinsic expiratory flow limitation
- Chronic obstructive pulmonary disease

- Dynamic hyperinflation
  - without intrinsic expiratory flow limitation
  - Breathing pattern and ventilator settings
    - Rapid breaths
    - High tidal volume
    - Inspiration greater than expiration
    - End-inspiratory pause
  - Added flow resistance
    - Fine-bore endotracheal tube
    - Ventilator tubing and devices

- Without dynamic hyperinflation
  - Recruitment of expiratory muscles
Auto PEEP

- Pressure (cm H₂O)
  - Progressively increasing end-expiratory alveolar pressure (intrinsic PEEP)

- Flow (L/min)
  - Incomplete emptying (gas trapping): expiratory flow is still occurring at the beginning of the next breath

- Volume (ml)
  - Progressively increasing end-expiratory volume (dynamic hyperinflation)

- Time (seconds)
Auto PEEP

Airway obstruction and intrinsic PEEP.

Airway pressure: 0 cm H₂O

Alveolar pressure: 5 cm H₂O

Pleural pressure: 4 cm H₂O

Pleural pressure during inspiratory effort: -6 cm H₂O

Air flow occurs because of the pressure gradient between airway pressure (0 cm H₂O) and alveolar pressure (-1 cm H₂O)

X+Y

X – normal amount of inspiratory effort
Auto PEEP consequences

• Ineffective triggers
• Increased WOB
• Hypoxia
• Barotrauma
• Hemodynamic instability
Auto PEEP detection

• End-expiratory occlusion is used to measure auto PEEP
• Pressure in the lungs equilibrates with the pressure ventilator circuit
• Pressure measured at the proximal airways is equal to the end-expiratory alveolar pressure
• Auto PEEP is the difference between total PEEP and set PEEP
Auto PEEP detection
Overcoming Auto PEEP

• Decrease
  • Insp time
  • RR
  • Vt
  • Resp demand – pain fever anxiety

• Bronchodilator use

• External PEEP
Ineffective trigger

- Respiratory muscular effort which is insufficient to initiate mechanical breath
- Manifests as a decrease in airway pressure associated with a simultaneous increase in airflow
- Ventilator factors—effort not able to meet the set trigger, large pressure drops across smaller tubes
- Patient related- Auto PEEP, resp muscle weakness and decreased drive
Ineffective trigger
Auto trigger

• Assisted breaths delivered which were not patient triggered

• Cause
  • Fluid in circuit, leak, cardiac oscillations, low trigger threshold
Double trigger

- Patients inspiration continues after the ventilator inspiration and triggers another breath immediately after the inspiration
  - High ventilatory demand of the patient (ARDS)
  - Inappropriate settings (Low tidal volume, short inspiratory time, high ETS)
Fig. 27. An example of double triggering in pressure support ventilation. Patient demand continues beyond the set inspiratory time, resulting in triggering of a second mandatory breath during the same patient effort.
Reverse triggering

• Unique type asynchrony in which diaphragmatic muscle contractions triggered by ventilator insufflations constitute a form of patient-ventilator interaction referred to as “entrainment”

• In heavily sedated patients it is suggested that patients had entrainment of neural breaths within mandatory breaths.

• This entrainment occurred at a ratio of 1:1 up to 1:3. They occur at the transition from the ventilator inspiration to expiration.

• Breath stacking, overdistention and VIDD
Reverse triggering
Reverse triggering
Flow asynchrony

• Causes:
  • High ventilatory demand (ALI/ARDS)
  • Low ventilatory settings (flow rate, Vt, Pramp)

• Treat:
  • Treat reversible causes (fever, acidosis)
  • Increase the Vt
  • Increase the flow rate (directly, or by decreasing inspiratory time, increasing pause)
  • Change to pressure control mode with variable flow
Flow asynchrony

Patient with ARDS weaning
Esophageal pressure curve

- Esophageal pressure is measured by a catheter with a balloon that is placed at the lower end of the esophagus
- Estimate the pleural pressure
- Passive patient esophageal pressure increases with each mechanical insufflation
- Spontaneously breathing patients esophageal pressure becomes negative during insufflation
- Positioning is key
Esophageal pressure curve
Positioning esophageal balloon
Positioning esophageal balloon
Esophageal waveform in passive patient
High Pes and Ptp
Ideal Ptp
Esophageal waveform in spontaneously breathing individuals

- Starts decreasing at the onset of the patient’s inspiratory effort and drops to a minimum pressure at the end of the inspiratory effort.
Esophageal and transpulmonary pressure waveforms spontaneous breathing
Clinical application

- Measuring transpulmonary pressure at end inspiration and expiration
- Open lung strategy in ARDS ventilation and prevention of lung injury
- End inspiratory transpulmonary pressure $\leq 25$ ($\leq 20$ cm)
- End expiratory transpulmonary pressure 0-5 cm
- Spontaneously breathing
  - Inspiratory effort
  - AutoPEEP
  - Asynchrony assessment
Inspiratory effort

• Shape of the decrease in esophageal pressure at the onset of the patient’s inspiratory effort provides info about the respiratory drive and the neuromuscular capacity.

**Strong inspiratory effort**

**Weak inspiratory effort**
Asynchrony
The most accurate method to quantify PEEPi is to measure the drop in esophageal pressure at end expiration at the point of the contraction of the inspiratory muscles until inspiratory flow starts.

Fig. 4. Airway pressure, flow, volume, and esophageal pressure ($P_{eo}$) waveforms in a patient with auto-PEEP. Note the decrease in $P_{eo}$ required to trigger the ventilator, which represents the amount of auto-PEEP. Also note that flow does not return to zero at the end of exhalation, and the inspiratory effort does not trigger the ventilator.
Pressure volume loop

• Positive pressure ventilation
  • Tracing begins in the lower left hand corner of the graph and moves counterclockwise
  • At end expiration, returns to the point of initiation
  • The highest point of the PV loop read off on the y-axis represents the tidal volume
  • The same point read against the x-axis represents the Ppeak
  • With exhalation, the tracing follows the expiratory curve downward, culminating at the point representing zero tidal volume and zero pressure (in the absence of set PEEP)
  • Change in volume per unit change in pressure - compliance
Pressure volume loop

Air–fluid interfaces within the lung generate forces of surface tension and the inspiratory and expiratory tracings follow different paths – tracing out a loop.
Pressure volume loop

- Traced clockwise
- Inspiration intrapleural pressure becomes negative → the tracing moves to the left of the y-axis and air is drawn into the lungs
- As TV is reached the lungs fill up with air and the negativity of the intrapleural pressure decreases the tracing returns to the zero pressure line
Pressure volume loop patient vs machine trigger

A. Machine triggered breath. Note the absence of a negative deflection

B. Patient-triggered breath. The drop in airway pressure prior to the positive pressure breath denotes the patient's triggering effort

Figure 8.19. The pressure-volume loop: triggering.
Pressure volume loop

**Figure 8.22.** Effect of decreased compliance on the PV loop during volume-targeted ventilation.

**Figure 8.23.** Effect of decreased compliance on the PV loop with pressure-targeted ventilation.

**Figure 8.25.** Pressure-volume loop of a highly compliant lung.
PV Loop high compliance COPD
Assessing recruitment using PV curve

• Normal lung – the PV curve is linear and the inflation and deflection curves are separated by small area of hysteresis
• Compliance remains constant
• Early ARDS the shape of the PV loop may differ
• The inflation and deflation limbs demonstrate a change in slope,
• Implication - respiratory-system compliance varies at different levels of pressure
• Hysteresis is greater than in normal-lung patients due to recruitment occurring during inflation and derecruitment occurring during deflation
Assessing recruitment using PV curve
Assessing recruitment using PV loop

• Linear compliance or midrange compliance
  • The compliance of the recruiting part of the inflation limb, i.e., between the two changes in the slope
  • The more vertical the slope, the more recruitment takes place
  • High linear compliance equates to high potential for recruitment
  • Lin Compliance of >50ml/cm H2O = recruitment maneuver

• Difference in volume between the inflation and deflection limb of curve at 20 cm H2O >400mL

• Concave inflation curve
Assessing recruitment using PV loop

Figure 3: Inflation limb showing upward convexity, indicating low potential for lung recruitment.

Figure 4: Inflation limb showing upward concavity, indicating high potential for lung recruitment.
PV Loop Difference at 20 cm less than 400
Flow-volume loop

• Loops with flow as a function of volume
• Inspiratory curve displayed above on ventilators
• Inspiratory flow rate is set and expiration is passive
• During inspiration - shape of the flow-volume loop is determined by the flow setting on the ventilator with volume-controlled ventilation
• During exhalation, the shape of the flow-volume loop is determined by respiratory mechanics
• Spontaneous breath is recognised by the slightly irregular contour of the inspiratory portion
Flow volume loop

Spontaneous breath is recognizable by the slightly irregular contour of its inspiratory portion

**Figure 8.31.** Flow–volume loop during volume controlled ventilation. (a) Sine-wave flow pattern. (b) Square-wave flow pattern.
Flow volume loop

**Figure 8.32.** Flow-volume loop: the effect of varying the set inspiratory flow rate during square-wave volume-targeted ventilation.

**Figure 8.34.** Flow-volume loop in pressure support ventilation. Note the abrupt decline in flow toward the end of ventilation as the ventilator cycles from inspiration to expiration (red arrow).
Flow volume loop

PCV: the peak flow is attained early during inspiration and the waveform shows a decelerating flow that is a defining characteristic of any pressure-targeted mode.
The waveform retains its typical morphology at all the levels of the pressure level.
Flow volume loop

**Figure 8.35.** Flow-volume loop: effect of increased airway resistance on flow and volume. Shown in the panel on the left is a normal looking flow-volume loop obtained during pressure-targeted ventilation. The effect of increased airway resistance is shown in the panel on the right. Both flow and volume have decreased.

**Figure 8.36.** Flow-volume loop: effect of increased inspiratory and expiratory resistance.
The expiratory flow tracing fails to return to the baseline at the end of exhalation (green line). The normal terminal part of the expiratory tracing is shown in blue.

The expiratory tracing stops well short of the y-axis; this can happen when there is air leakage ET cuff leak. Volume of leak can be quantified from graph.
Air trapping and Leak
Flow volume loop

**Figure 8.48.** Flow-volume loop: effect of a decrease in compliance.

**Figure 8.52.** Flow-volume loop: active exhalation. Inspiratory tidal volume ($V_{in}$) is shown by the red arrow, and expiratory tidal volume $V_{ex}$ by the green arrow.
Flow volume loop

Flow asynchrony during inhalation

Flow asynchrony during exhalation
Summary

• Ventilator waveform analysis is a very integral and important component in the management of a mechanically ventilated patient

• Significance of scalars vary based on the mode of ventilation, the independent and dependent variable

• Overall scalars and loops provide valuable information wrt the ventilator patient interaction includes synchrony, respiratory system mechanics and circuit related issues (secretions, leaks)

• Early interpretation and corrective measures essential for optimal ventilation