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Peri-operative spirometry : tool or gadget ?

J. G. M. VAN LIMMEN and L. L. SZEGEDI

Abstract : More and more anesthesia machines are foreseen with spirometry monitoring. Nevertheless, the use of such equipment needs some interpretation skills for the displayed curves and numerical values otherwise it remains just a disturbing gadget rather than a powerful tool. This review explains in his first part the basic principles of interpretation of the spirometric data, and in the second part gives concrete examples of clinical situations.

I. INTRODUCTION

“Tool : (*noun*) a thing that helps you to do your job or to achieve something”

“Gadget : (*noun*) a small mechanical device valued for its novelty or ingenuity”

(*Oxford Advanced Learner's Dictionary of Current English*, Oxford University Press, 7Rev ed., 2006)

Before anesthesia, assessment of the lung function can be obtained by using pre-operative spirometry. This widely used technique is well known by most physicians and is an important tool for differential diagnosis between obstructive or restrictive lung diseases. During general anesthesia the patient's respiratory status changes quickly or requires frequent adjustments in ventilatory parameters. Arterial blood gases and capnography are frequently used to monitor patients' ventilatory properties. Intermittent monitoring of the mechanical ventilation during anesthesia is sometimes insufficient in patients with important pulmonary diseases or undergoing complex thoracic surgery. These patients require optimal ventilatory support in order to reduce peri-operative and post-operative complications. Spirometry can be used as online monitoring of the respiratory function. It continuously measures the respiratory function and is therefore a dynamic monitoring tool. Spirometry data provide important information about the peri-operative lung function (1).

II. DEFINITION OF SPIROMETRY

Spirometry is a non-invasive monitor device which measures volume, pressure and flow in the airway.

These measurements may be used to construct a pressure-volume curve (PV) and a flow-volume curve (FV). The constructed curves will give important information about the peri-operative respiratory function (2).

III. RESULTS

A. Pressure-Volume curve

General principles

Both lung and thoracic wall have elastic properties. The compliance or distensibility is used to measure the elastic recoil of both lung and thoracic wall. The compliance is calculated by the change in lung volume divided by the change in distending pressure ($\Delta V/\Delta P$). The total compliance of the respiratory system is obtained considering both lung- and thoracic wall compliance. For normal lung and chest wall, changes in volume (ΔV) per unit change in pressure (ΔP) have a sort of linear relationship through the tidal volume range. Peri-operative spirometry will measure the total compliance of the respiratory system by plotting, volume against pressure creating a pressure-volume (PV) curve (Fig. 1). The linear relationship between pressure and volume may be characterized by the total compliance of the respiratory system. A normal value for the total compliance of the respiratory system is 100 ml/cmH₂O (3,4).

Jurgen G. M. VAN LIMMEN, M.D., Staff Anesthesiologist ;
Laszlo L. SZEGEDI, M.D., PhD, Staff Anesthesiologist.
Department of Anesthesiology, Ghent University Hospital,
Ghent, Belgium.

Correspondence address : J. G. M. Van Limmen, Department
of Anesthesiology, Ghent University Hospital, De Pintelaan
185, 9000 Ghent, Belgium. Tel. : 0032-93325805.
Fax : 0032-93324987.
E-mail : Jurgen.vanlimmen@uzgent.be

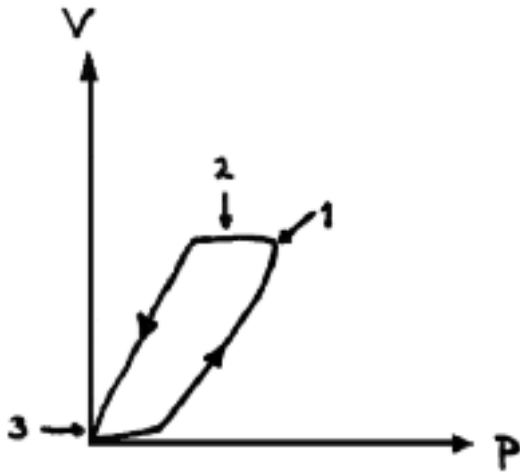


Fig. 1. — Normal pressure-volume curve.

• Normal PV curve. The P on the horizontal scale represents the pressure and the V on the vertical scale represents the volume. The curve runs counter-clockwise. The end-inspiratory pressure (1), the plateau pressure (2) and end-expiratory pressure (3) can be distinguished. There is a linear relationship between the pressure and the volume that characterises the total compliance of the respiratory system.

Controlled ventilation & pressure-volume curves

During mechanical ventilation the tidal volume (V_t) is used for ΔV . If an inspiratory pause is used, which is sufficient enough to produce a plateau phase the ΔP_{alv} can be calculated as the difference in alveolar pressure at the two extremes of the tidal volume ($P_{Plateau} - PEEP_{Tot}$), where $P_{Plateau}$ is the end-inspiratory plateau pressure and $PEEP_{Tot}$ is the total positive end-expiratory pressure. No gas flow is measured during the plateau phase, in which case $P_{Plateau}$ approximates the intra-alveolar pressure (P_{alv}). The slope of the pressure-volume curve represents the compliance of the respiratory system. The compliance can be determined by spirometry using the following equation :

$$C_{RS,ST} = V_{te} / (P_{Plateau} - PEEP_{Tot})$$

Where $C_{RS,ST}$ is the static compliance of the respiratory system, V_{te} the expired tidal volume and $PEEP$ the total (intrinsic and extrinsic) end-expiratory pressure.

Since the obtained compliance is measured during respiration, the slope of the pressure-volume curve is a dynamic measurement and called the dynamic compliance of the respiratory system (4).

Hysteresis

During inflation, the lung and chest wall expands, and alveolar recruitment ensues. A reverse

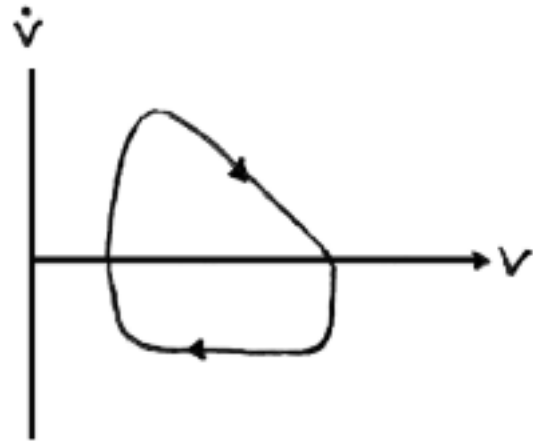


Fig. 2. — Normal flow-volume curve.

• Normal FV curve. On the horizontal scale the V represents the volume, while on the vertical scale the flow is shown. The loop runs clockwise. The bottom half of the curve represents the inspiratory limb, the top half of the curve represents the expiratory limb. The apex of the FV curve represents the peak-expiratory flow (PEF).

phenomenon occurs during deflation and derecruitment occurs. This phenomenon is called hysteresis.

In spontaneously breathing patients, the surface area between the inflation and deflation limb is related to the lung tissue characteristics, surface tension and the number of open lung units.

In intubated patients the surface area is mainly a function of airway resistance, and influenced by the resistance of the endotracheal tube (ETT) (2, 3).

B. Flow-volume curve

General principles

Inspiratory gas flow during mechanical ventilation is ensured by positive pressure ventilation. During expiration gas flows out of the lungs, driven by the elastic recoil of the respiratory system. When gas flow is plotted against volume during mechanical ventilation, a flow-volume (FV) curve is constructed (Fig. 2). Data obtained from this curve can give important information about the mechanical properties of the respiratory system (4).

The horizontal line is the volume scale, starting at the zero volume point at the right. The loop is traced in the clockwise direction. During inspiration, it moves to the left with an increase in volume and inspiratory flow. Expiratory flow is the volume of gas exhaled over a period of time, with volume decreasing for positive expiratory flow.

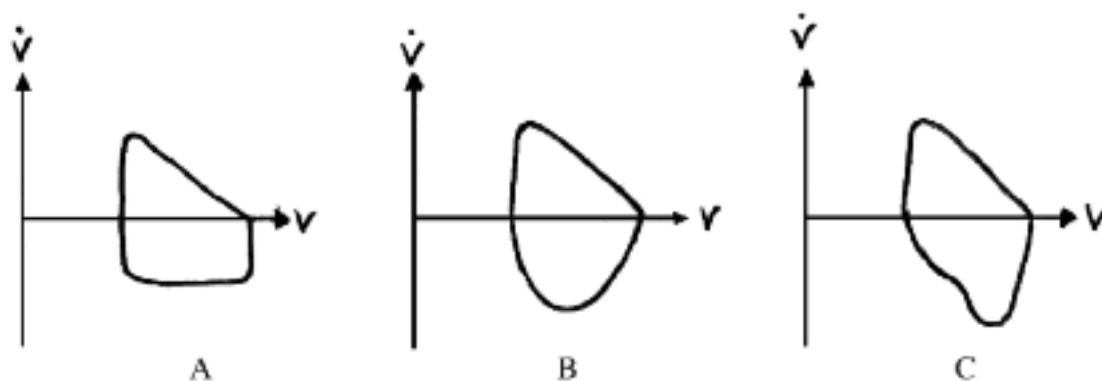


Fig. 3. — Flow-volume curves obtained with various inspiratory flow patterns.

• Three different FV curves with various inspiratory flow patterns. Reading from left to right. A : FV curve with square flow, B : FV curve with variable flow, C : FV curve with pressure preset ventilation.

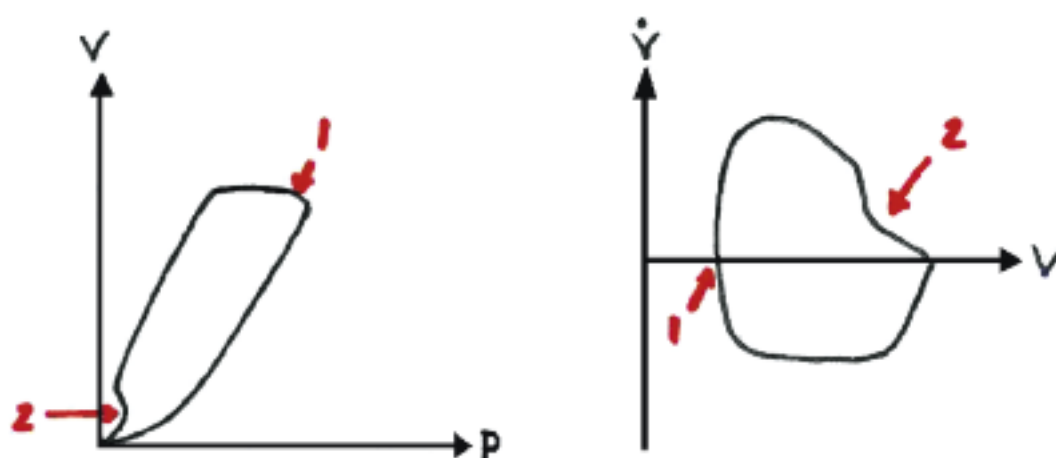


Fig. 4. — Anesthesia ventilator with descending type bellows.

• This figure shows a PV- and FV-curve of an anesthesia ventilator using a descending type bellow. This figure shows the end-inspiratory pause (1) and the typical end-expiratory crease of the bouncing bellows (2).

The bottom half of the curve represents the inspiratory limb, which has a slightly rectangular shape. The top half of the curve represents the expiratory limb of the respiration, which has a triangular shape. The apex of the FV curve represents the peak expiratory flow (PEF) (Fig. 2) (2, 4).

The magnitude and the shape of the inspiratory limb are affected by the inspiratory flow pattern of the ventilator and not by the respiratory system (airways and alveoli) of the patient (Fig. 3) (5).

Anesthesia ventilators contain descending or ascending bellows. Descending type ventilator bellows fall down passively during expiration and bounce slightly as they come to stop, causing an end-expiratory crease on the PV and FV curves (Fig. 4). Some anesthesia ventilators have a built-in end-inspiratory pause, when positive pressure is maintained in the circuit and the peak inspiratory

pressure (P_{Peak}) decreases by 3-5 cmH₂O to the $P_{Plateau}$ (4, 5).

Passive expiratory volume (PEV)

Passive expiratory volume (PEV₁) represents the volume exhaled during the first second of passive deflation. PEV₁ reflects the same intrinsic properties of the respiratory system (elastic recoil of the lungs, airway resistance and collapsibility of the airway) as the forced expiratory curve. In theory, this method should provide a representative estimation of the airway resistance but its value is strongly influenced by the resistive properties of the ETT. The ETT is connected in series with the patients' airways. The ETT is a non-linear, flow-dependent resistance and its flow resistive characteristics are influencing the mechanical properties

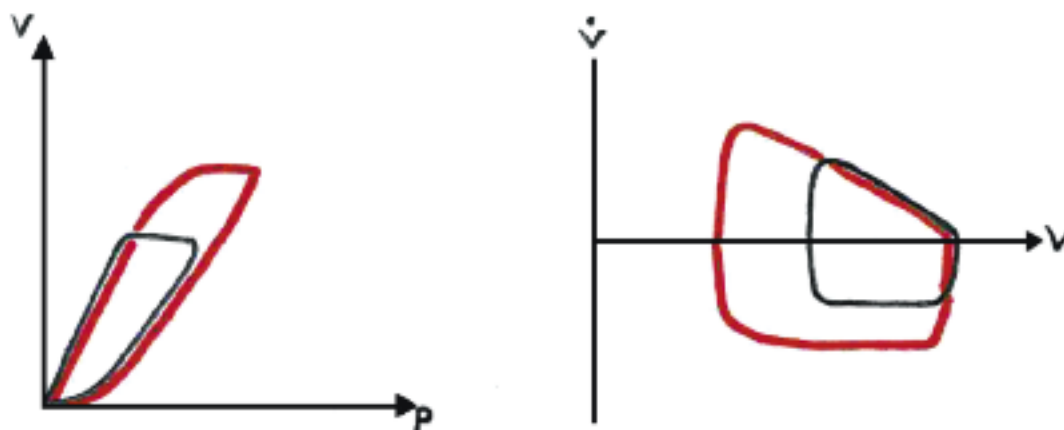


Fig. 5. — Effect of increasing tidal volume.

• Effect of increasing the V_t . The PV curve shows a cranial shift. The FV curve has a larger surface area. Notice that the compliance of the respiratory system does not change.

of the respiratory system. The properties of ETT affect the expiratory flow and may contribute to dynamic hyperinflation and accounts for more than 50% of the PV loop area. This effect is more pronounced during expiration than inspiration (2, 4).

C. Pressure controlled and variable flow mechanical ventilation

A particular situation is when using pressure-controlled mechanical ventilation, or the case of anesthesia ventilators using variable inspiratory flow in order to obtain a targeted end-tidal CO₂ pressure. In the case of pressure controlled mechanical ventilation, inspiratory flow is variable, not constant (Fig. 3B).

A comparable but not similar situation is when variable flows are used; the shape of the FV curve is like those during pressure controlled mechanical ventilation. Nevertheless, the acquisition of a reference, baseline loop, for comparisons, is not possible, and characteristic shapes for a precise situation are lacking.

D. Characteristic pressure-volume and flow-volume curves

During mechanical ventilation, spirometry can be used as a tool for measuring the mechanical properties of an individual patient. There are large inter-individual variations for any given PV or FV curve. In normal patients, both curves are influenced by the respiratory rate, lung volume and I/E ratios (Fig. 1, 2) (2).

Effect of tidal volume

Tidal volume has an effect on the relative lung volume. By increasing tidal volume, the PV curve has a cranial shift. However the compliance of the respiratory system does not alter. Looking at the FV curve, it appears to have a greater surface area (Fig. 5) (4, 5).

Effect of decreasing functional lung units

After lobectomy there is a decrease in the number of functional lung units. A decrease in lung volume is accompanied by an increase in airway resistance. To maintain the same tidal volume, a greater airway pressure must be applied (Figs. 6, 7) (4).

Effect of respiratory frequency

For the same minute ventilation, increasing the respiratory frequency will lead to smaller tidal volumes, which can be detected by spirometry (6).

Effect of I/E ratio

Increasing the inspiratory time will lead to a reduction of expiratory time. In extreme cases, prolonged inspiratory time can lead to increasing hyperinflation and the occurrence of air-trapping and intrinsic PEEP (PEEP_i) (Fig. 10) (6, 7).

E. Spontaneous respiration

During spontaneous breathing with an ETT in place both curves change. The FV curve has an oval

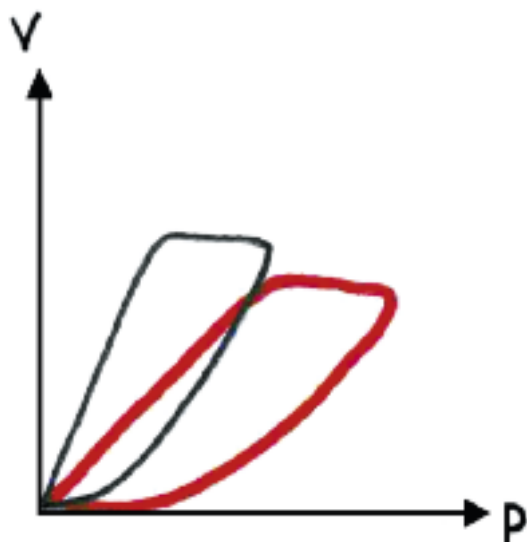


Fig. 6. — Effect of decreased compliance of the respiratory system : the pressure-volume curve.

- Effect of decreased functional lung units. This occurs during surgical manipulation, in obese patients or during pneumoperitoneum. The PV loop has a right- and downward shift : to maintain the same V_t , a greater airway pressure must be applied.

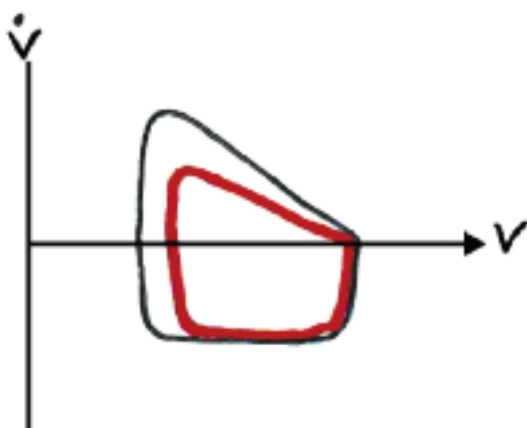


Fig. 7. — Effect of decreased compliance of the respiratory system : the flow-volume curve.

- Effect of decreased functional lung-units. On the FV curve there is a reduction in expiratory flow. The peak expiratory flow (PEF) is reduced.

pattern without an expiratory flow peak. The PV curve is reversed, runs clockwise, and in case of sufficient inspiratory force, the inspiratory ascending limb is in the “negative pressure” zone (Fig. 8). Spirometry can be used to determine the inspiratory force and the time to extubate a patient (2, 4).

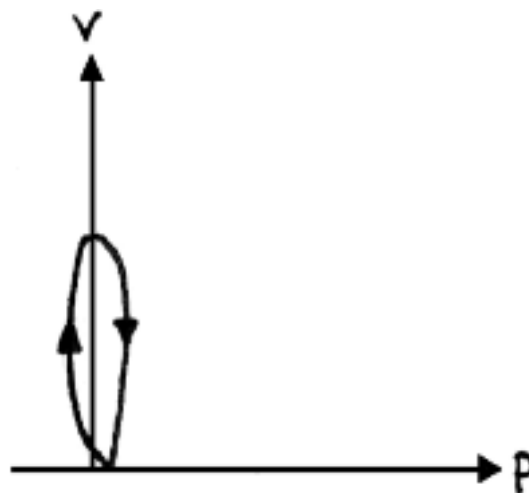


Fig. 8. — Spontaneous respiration.

- Effect of spontaneous breathing with an ETT in place. The PV curve is reversed. If the patient has sufficient inspiratory force, the inspiratory ascending limb is in the “negative pressure” zone in which extubation is possible.

F. Anesthetic implications of spirometry during controlled ventilation

General principles

As described above, spirometry is a powerful tool to monitor the respiratory mechanics during controlled ventilation. The effect on ventilation when an adjustment of tidal volume, respiratory frequency or I/E ratio occurs can easily be monitored (3, 8).

1. Intubation difficulties

Spirometry can be used as a control tool mechanism for positioning of the ETT. In normal patients with a correct positioning of the ETT a PV curve and FV curve will appear on the monitor (Figs. 1, 2) (2).

- Endobronchial intubation will ventilate one lung only. A reduction in lung units will lead to increased airway pressure and a reduction in total lung compliance. On the PV loop a right- and downward shift will occur and on the FV loop a decreased expiratory flow will be seen (Figs. 6, 7) (6, 8).
- Esophageal intubation is easily detected when using spirometry. On the PV loop a large inspiratory pressure will be necessary to deliver only a small volume in the non-compliant esophagus. On the FV loop an irregular inspiratory and expiratory flow will be seen (Fig. 9) (2).

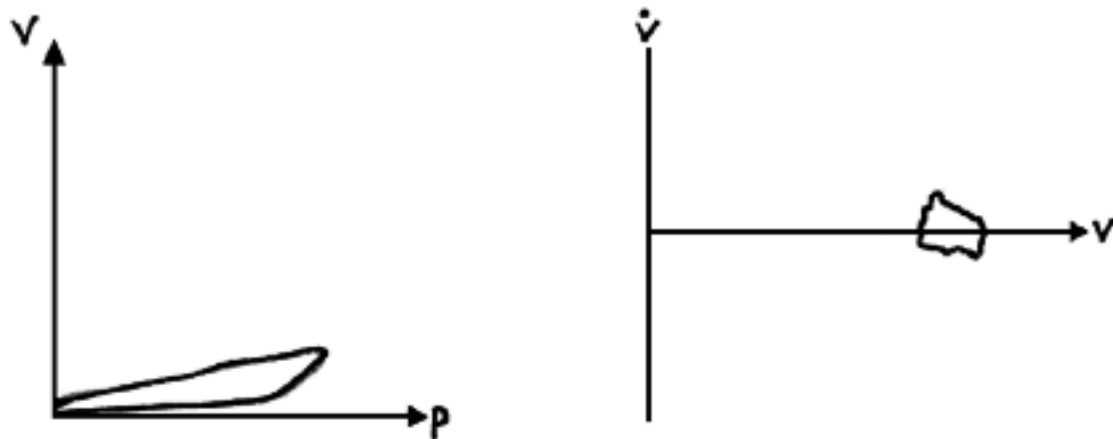


Fig. 9. — Oesophageal intubation.

• Effect of oesophageal intubation. The PV loop is shifted to the right and downward. A large inspiratory pressure is needed to create small V_i . The FV curve shows irregular inspiratory and expiratory flow.

- Tracheal tube kinking after induction of anaesthesia will lead to high inspiratory pressure. On the PV loop there is a right shift and an enlarged area of the PV curve. On the FV loop both inspiratory and expiratory flows are diminished (Figs. 6, 7) (2, 6, 8).
- Bronchospasm is a serious peri-operative respiratory complication which needs immediate treatment. During bronchospasm, a reduction in airway calibre will occur, leading to high inspiratory pressure. On the PV loop a right shift can be observed while on FV loop both inspiratory and expiratory flow reduction is seen (Fig. 14) (2, 4).

2. Postural changes

Patients who receive controlled ventilation show a reduction in total respiratory compliance during Trendelenburg tilt. Head-down position causes the abdominal viscera to shift cranial and a cranial shift of the diaphragm. A reduction in lung volume will lead to a reduction in total lung compliance, therefore shifting the PV loop to the right (Fig. 6, 7) (9).

3. Chronic obstructive pulmonary disease (COPD)

Spirometry is also very useful in COPD patients. Patients with COPD are more at risk for peri-operative and post-operative pulmonary complications. Adequate ventilatory support during general anaesthesia is crucial in order to reduce pulmonary complications. Spirometry can be used to monitor the respiratory mechanics during controlled ventilation (1).

- Chronic bronchitis is characterized by hypertrophy of the mucus cells and ciliary cell dysfunction leading to increased production of sputa and loss of elastic recoil. The typical chronic bronchitis patient is the “blue bloater” who has an important level of dyspnoea and cyanosis. COPD patients have important ventilation/perfusion mismatch (V/Q mismatch) with more hypoxemia and hypercapnia (1).
- Emphysema is characterized by destruction of alveolar wall with loss of elasticity and air trapping. The typical emphysema patient is the “pink puffer” who develops more dyspnoea than a blue bloater. Emphysema patients have an important increase in physiological dead space (1).

Both emphysema and chronic bronchitis cause a reduction in expiratory flow rates. The expiratory flow limitation results in air trapping and the development of $PEEP_i$. Diagnosis of $PEEP_i$ is difficult but spirometry can be helpful to detect it (1, 4, 7).

On the FV curve the expiratory limb does not reach zero, resulting in $PEEP_i$ (Fig. 10) (7).

On the PV curve a distinction between emphysema and chronic bronchitis can be made. With emphysema the PV loop is displaced to the left and steeper than in normal patients. With chronic bronchitis an increase in airway resistance is seen, by which the PV loop becomes enlarged and shifted to the right (Figures 11, 12) (2, 3).

Cystic fibrosis is a genetic disease characterized by mucus accumulation, bronchitis, bronchiectasis and dynamic hyperinflation. On the PV loop there is a shift to the right and on the FV loop expiration is incomplete leading to $PEEP_i$ (1, 2, 7).

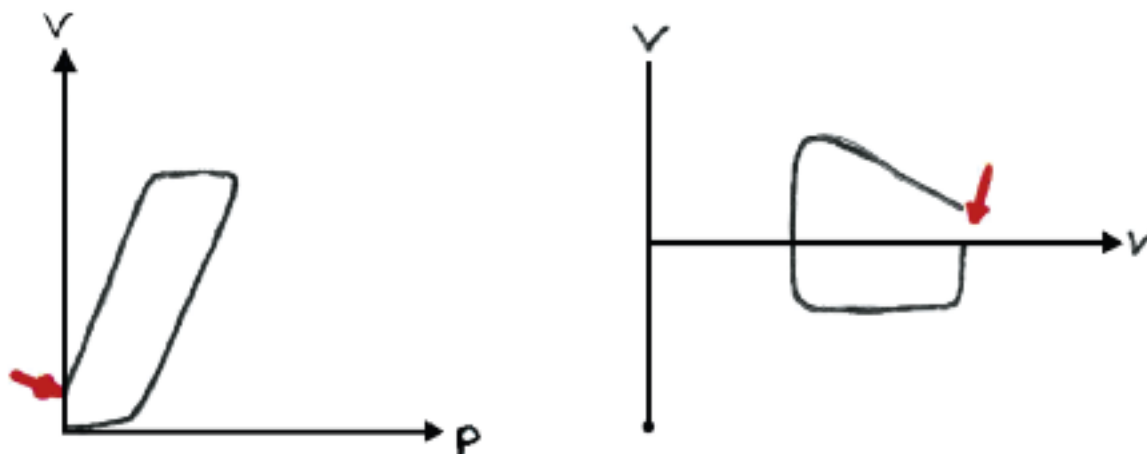


Fig. 10. — Intrinsic PEEP.

• Patients with COPD have a reduction in expiratory flow rates. The expiratory flow rate reduction can result in air trapping and the development of PEEP_i. On both PV and FV curve the expiratory limb does not reach zero, resulting in PEEP_i.

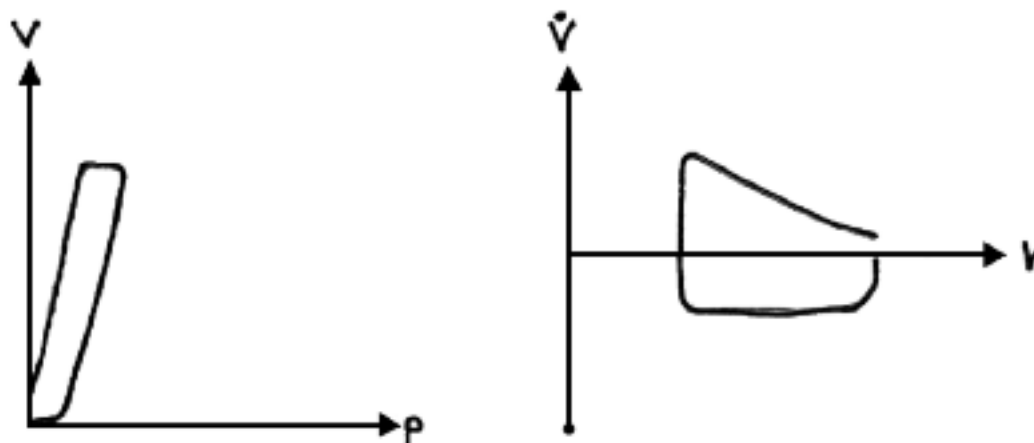


Fig. 11. — Emphysema.

• Emphysema patients have specific PV and FV curves. On the PV curve the loop is displaced to the left and steeper. On both curves PEEP_i will be registered.

4. Pneumoperitoneum

Spirometry is also very useful during specific types of surgery. Laparoscopic procedures are accompanied by pneumoperitoneum which has an important influence on the respiratory system. During pneumoperitoneum the intra-abdominal pressure rises significantly. The increase in intra-abdominal pressure leads to a reduction in compliance of the respiratory system. High inspiratory pressures are needed to maintain tidal volume (Figures 6, 7) (10).

5. One-lung ventilation

Spirometry can be used to diagnose double-lumen endotracheal tube (DLT) malposition during

one-lung ventilation. Migration of a DLT can occur during positioning of the patient or during surgical manipulation. A DLT can either be not far enough or to deeply placed in the bronchus. In the latter case a lung lobe is not ventilated (or insufficiently ventilated). Due to a narrow margin of safety even a correctly placed DLT may be displaced by changing patient's position but also by surgical manipulation (6, 7).

- If a correct positioning of DLT is obtained, a right shift on PV loop occurs. On the FV loop minimal changes occur, but both inspiratory and expiratory flow are reduced (Fig. 13) (6, 7).
- If a DLT is malpositioned, a significant right shift of the PV loop occurs which leads to high

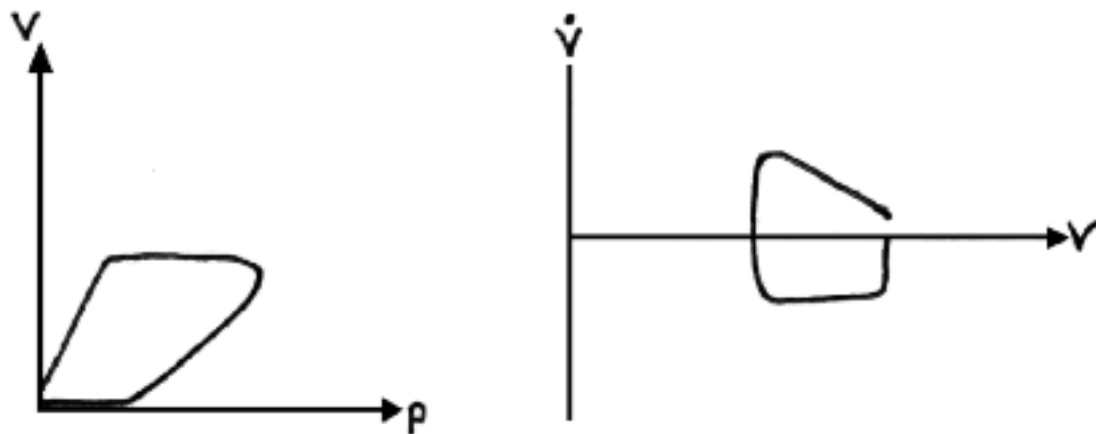


Fig. 12. — Chronic bronchitis.

• Patients with chronic bronchitis have increased airway resistance. The PV loop is enlarged and shifted to the right. On both curves $PEEP_i$ will be registered.

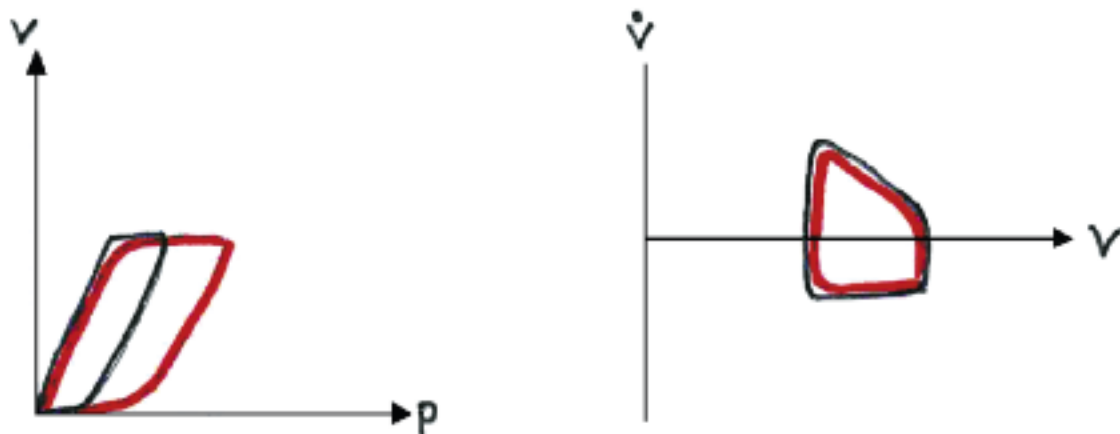
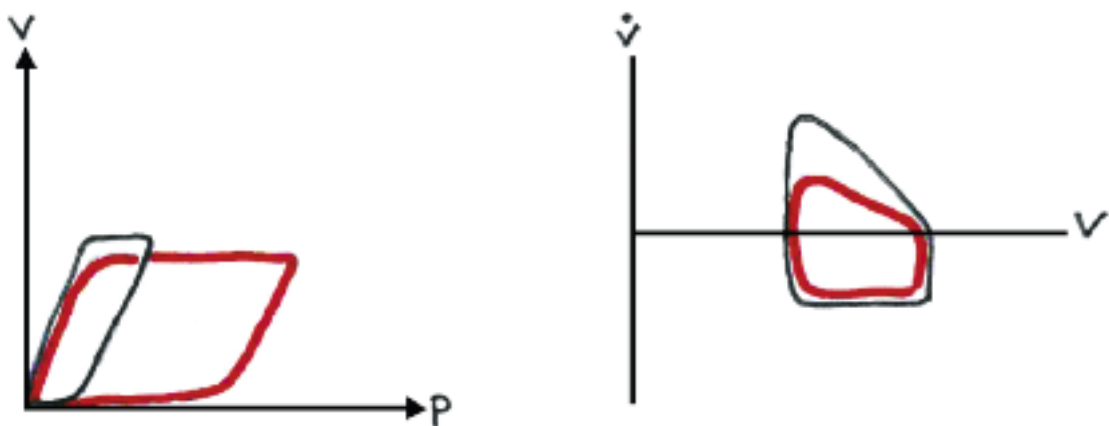


Fig. 13. — Double lumen endobronchial tube malposition.

• Correct placement of a DLT. If one-lung ventilation is started, there is a reduction of function lung units. On PV curve a rightward shift occurs. On the FV curve minimal changes occurs. However both inspiratory and expiratory flow are reduced.



• Malposition of a DLT. If the DLT is too deep in the bronchus, high inspiratory pressures are needed to maintain V_t . On the PV curve there is a rightward shift of the PV loop and on FV curve a reduction of PEF is seen.

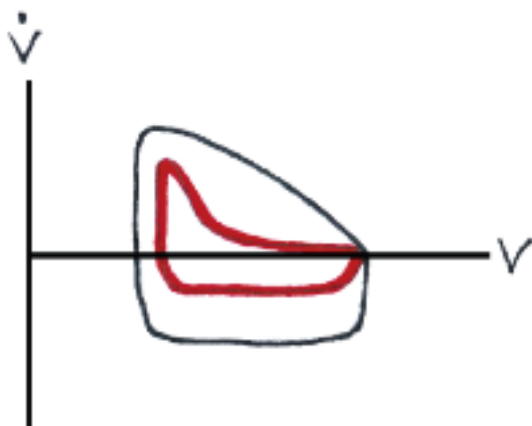


Fig. 14. — Bronchospasm.

- FV curve during bronchospasm. The FV loop has a typical amputated end-expiratory flow.

inspiratory pressures to maintain tidal volume. On the FV loop a reduction in PEF is seen (Fig. 13) (6, 7).

6. Surgical manipulation

Surgical manipulation of the non-dependent non-ventilated lung during thoracic surgery has an important effect on the peri-operative mechanical properties of the dependent ventilated lung. There is an important risk of PEEP_i development during this manipulation. Spirometry can be used to monitor peri-operative ventilation. On the flow-volume curve, both inspiratory and expiratory flows are altered by surgical manipulation (Fig. 6, 7) (6, 7).

During abdominal surgery, the abdominal retractors can compromise the function of one hemithorax. On spirometry, the pressure-volume curve is shifted to the right with increase inspiratory pressure. On the FV curve expiration may be incomplete leading to PEEP_i (6, 7).

IV. CONCLUSION

Continuous monitoring of the mechanical properties of the respiratory system by spirometry and its pressure-volume curves and flow-volume curves can be very helpful for respiratory management of patients during anesthesia. Adjustments of ventilation and its effect on patients' respiratory function can be monitored by spirometry. An alteration in configuration of pressure-volume and flow-volume loops complements and precedes detection of abnormalities.

High risk patients, with chronic lung disease, can be effectively monitored by spirometry during the peri-operative period. An optimal ventilatory support will reduce peri-operative and post-operative pulmonary complications in these patients. Therefore routine spirometry should be advised to be used in these patients.

Several surgical procedures are more at risk of pulmonary complications. Laparoscopic procedures with increased intra-abdominal pressure can lead to significant pulmonary complications. Adequate monitoring of the respiratory function and mechanical properties are important.

Thoracic surgery is probably the most important surgical risk factor for peri-operative and post-operative pulmonary complications (11). Malpositioning of DLT does occur quite frequently. Spirometry can be used to diagnose DLT malpositioning and for optimal peri-operative monitoring of the respiratory function.

Other applications, such as monitoring of muscular strength and residual curarisation at emergence from general anesthesia in a patient breathing spontaneously, is a future perspective.

Spirometry is a powerful tool for peri-operative monitoring of the dynamic mechanical respiratory function. However, without a good knowledge of the normal pressure-volume and flow-volume curves to understand the obtained curves, it remains just a gadget.

V. ADDENDA

Abbreviations

$C_{RS,ST}$	Static compliance of the respiratory system.
DV	Changes in volume.
DP	Changes in pressure.
DLT	Double-lumen endobronchial tube.
ETT	Endotracheale tube.
FV curve	Flow-volume curve.
I/E ratio	Inspiratory/expiratory ratio.
P_{alv}	Alveolar pressure.
P_{Peak}	Peak pressure.
$P_{Plateau}$	Plateau pressure.
PEEP _{Tot}	Total positive end-expiratory pressure.
PEEP _i	Intrinsic PEEP.
PEF	Peak expiratory flow.
PEV ₁	Passive expiratory volume exhaled in the first second.
PV curve	Pressure-volume curve.

V_t Tidal volume.
 V/Q mismatch Ventilation/perfusion mismatch.

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