R-V graph in whole body plethysmography

Hans-Juergen Smith
Product Manager, Respiratory Diagnostics, Vyaire Medical

Darren Murray
Clinical Application Specialist

Introduction

Slow spirometry and forced spirometry *(flow volume loop)* are often used to measure clinically relevant lung volumes and forced expiratory and inspiratory flows. Dynamic parameters, such as forced expiratory volumes in one second (FEV1) or forced vital capacity (FVC) and static lung volumes, such as expiratory reserve volume (ERV), inspiratory capacity (IC) and inspiratory vital capacity (IVC) can be derived.

The influence of patient cooperation has to be considered on the quality of spirometry test results, which are highly effort-dependent. Furthermore, maximal inspiratory and expiratory maneuvers do not specifically represent resting tidal breathing conditions, and therefore can lead to diagnostic uncertainties.

Whole body plethysmography allows comprehensive tidal breathing analysis based on the determination of resistance in the airways (*R*aw) and the lung volume at the end of a tidal volume expiration.[1,2] This is the point when the lung inward and chest wall outward elastic recoil forces are at an equilibrium, which is termed as functional residual capacity (FRCpleth) or intrathoracic gas volume (ITGV). If the measured FRCpleth is then linked with an additional maximal vital capacity maneuver, further absolute lung volumes, such as total lung capacity (TLC) and residual volumes (RV) can be determined. The ratio between lung volumes at tidal breathing and total lung capacity (RV/TLC) can be calculated.

A newly developed clinically oriented graphic report, the resistance-volume graph (R-V graph), displays the course of resistance in the airways (*R*aw) when lung volumes are considered through the tidal breathing cycle (VT). The R-V graph is based on conventional indices, such as *R*aw and FRCpleth, and its generation requires neither modifications in the testing procedure nor changes in the application of current interpretation concepts in body plethysmography. The design also utilizes predicted ranges, and therefore uniquely combines all relevant body plethysmography test results for quick and reliable visual diagnosis.

s*R*aw breathing loops using full body plethysmography

In the first phase of the plethysmography measurement, the patient is breathing normally while sitting in a tightly sealed box. Breathing loops of the patient’s specific airway resistance (s*R*aw loops) are recorded and compensated for body conditions (BTPS). The slope of the breathing loops can be calculated using different slope integrating lines *(Figure 1)*.

Slope fitting according to Matthys is called effective specific airway resistance (s*R*eff).[3] This method provides the lowest variability as it incorporates area indices of the entire breathing loop. Due to this feature, s*R*eff is often used in clinical data trending.

Another established method for s*R*aw slope fitting was outlined by Ulmer, which is termed as total specific airway resistance (s*R*tot).[4] Ulmer defines a line between the points of maximal in- and expiratory shift volume. This method brings the advantage of improved sensitivity in end-expiratory inhomogeneity within the peripheral lung; however, it is associated with increased variability.

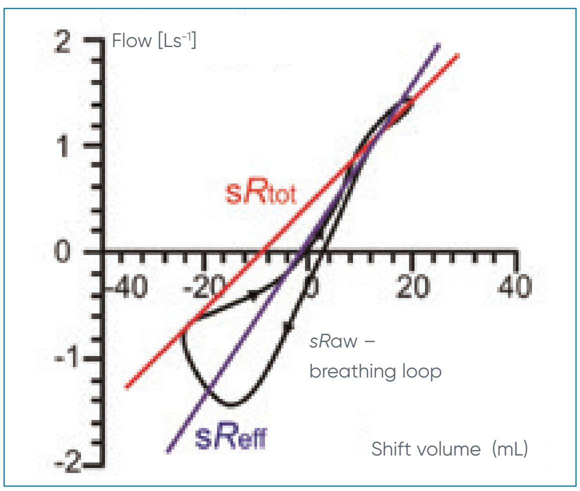

Figure 1: The s*R*aw breathing loop and two of its common slope integrating lines:

- s*R*eff: Effective specific airway resistance
- s*R*tot: Total specific airway resistance

Specific information regarding the changes in airway resistance across the entire breathing cycle as well as its direct relationship to the lung volume at any point of measurement are included in the s*R*aw breathing loop. However, the way this is displayed plotting flow against shift volume lacks details due to the nature of this flow-“shift volume”-diagram *(Figure 1)*, which does not incorporate differentiable features of airway resistance and lung volume.

It is important to appreciate that the s*R*aw slope provides only an average measure throughout the breathing cycle. Therefore, the degree of ventilation inhomogeneity, expiratory flow limitation or end-expiratory closing within the airways may not be identified. Furthermore, a collapse in the peripheral lung during expiration within the tidal breath can be underestimated. The specific changes caused by obstruction during the tidal breath may also not be observed. In summary, the mechanisms of obstruction lack detail using this non-specific loop.

Measurement of lung volumes using full body plethysmography

Absolute lung volumes, such as functional residual capacity (FRCpleth), residual volume (RV) and total lung capacity (TLC) can be accurately measured using whole body plethysmography, allowing the evaluation of the peripheral lung. These volumes cannot be determined from a spirometry measurement alone and require a “linked maneuver” in which the FRC shutter measurement is linked with a maximal slow or forced spirometry breathing *(Figure 2)*.

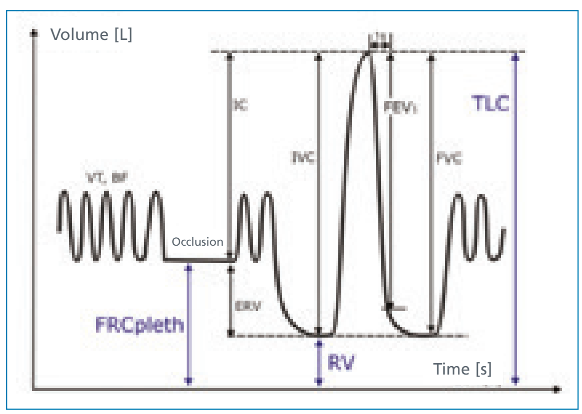

Figure 2: In the course of a “linked maneuver,” the measurement of FRCpleth volume is linked with a maximal maneuver so that the following absolute volumes can be derived:

- FRCpleth: Functional residual capacity
- RV: Residual volume
- TLC: Total lung capacity

Airway resistance (*R*aw) using full body plethysmography

The effective airway resistance (*R*eff) and the total airway resistance (*R*tot) are automatically calculated from the corresponding specific airway resistances (s*R*eff, s*R*tot) relative to the mean lung volume at resting breathing. Measured FRCpleth, therefore, has to be increased by half of tidal volume (VT) outlined in the equation below.

$$Raw = \frac{sRaw}{FRCpleth + \frac{VT}{2}}$$

Due to how *R*aw is calculated from s*R*aw and FRCpleth, *R*aw is simply an average of the airway resistance throughout the tidal volume cycle. Thus, changes in total cross sectional airway caliber affecting resistance to flow within tidal breathing is dependent on physiologic and pathophysiologic characteristics of the respiratory system that cannot be shown.

The concept of resistance-volume analysis

The graphical display of the test results using whole body plethysmography today is similar to that originally outlined by DuBois and co-authors more than 50 years ago.[1,2] Islam and Ulmer in 1977 suggested plotting the behavior of airway resistance against the corresponding lung volume.[5] They discovered this method is both reproducible and informative. Specific patterns of flow and/or volume-dependent variations in airway resistance, differentiated between inspiration and expiration, can be detected.

> *"It is important to note that the testing procedure in clinical routine diagnostics remains unchanged as the R-V graph plots currently measured data of Raw with respect to measured lung volumes."*

In order to allow a wider and more in-depth diagnostic image of airway resistance during quiet tidal breathing, the relationship between airway resistance and lung volumes with reference to predicted values can now be displayed. Using the recorded body plethysmography signals of flow, volume and shift volume with respect to absolute lung volumes of RV, FRCpleth and TLC, the R-V transformation (resistance-volume transformation) generates instantaneous loops over the course of airway resistance relative to absolute lung volume termed as the R-V graph *(resistance-volume graph; Figure 3)*.

It is important to note that the testing procedure in clinical routine diagnostics remains unchanged as the R-V graph plots currently measured data of *R*aw with respect to measured lung volumes.

R-V transformation

The R-V transformation integrates the specific airway resistance (s*R*aw) loops recorded during tidal breathing prior to the occlusion of the shutter *(Figure 3a)* with the occlusion pressure curves (FRCpleth) recorded during the occluded shutter *(Figure 3b)*. The data is also smoothed using the average of the accepted breathing loop curves (s*R*aw) and the median of the valid FRCpleth slopes. A simple algorithm is then applied to generate the R-V graph *(Figure 3c)* by linking data from the measured signals.

Figure 3a:
s*R*aw breathing loops:

The entire courses of all valid breathing loops are averaged.

Figure 3b: FRC occlusion pressure curves:

The median of all accepted FRC recordings is used and linked with maximal breathing from RV to TLC.

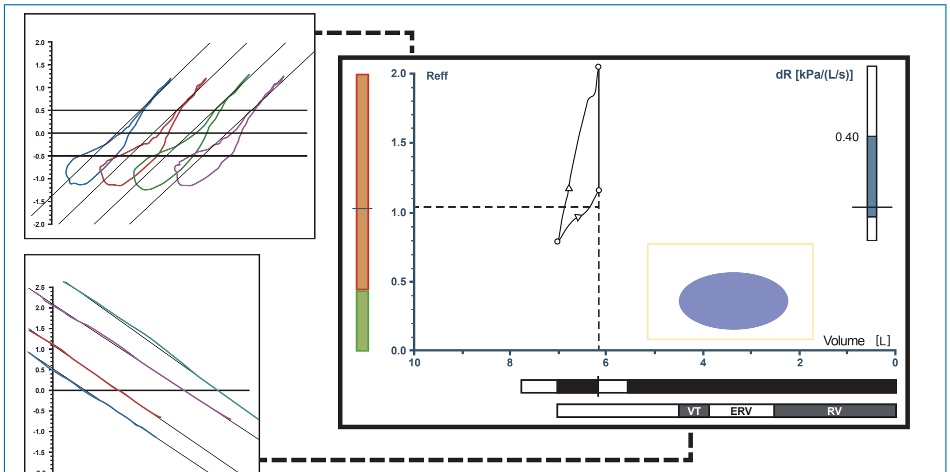

Figure 3c: R-V graph: Resistance volume dependence

Figure 3: By means of an R-V transformation, the recordings during the first and second phases of the whole body plethysmography measurement *(Figure 3a and 3b)* are linked into the R-V graph *(Figure 3c)*.

The components of the R-V graph

There is always a relationship between airway resistance and lung volume. The *R*aw is never constant. During tidal breathing, the airway caliber and therefore airway resistance (*R*aw), is affected by both airway smooth muscle tone and elastic recoil properties, which can cause airways to collapse and significant increases in *R*aw on expiration. In chronic obstructive pulmonary disease (COPD), the peripheral collapse is largest at FRC, e.g., *R*aw differs maximally between the end of expiration and the beginning of inspiration.

The R-V graph *(Figure 4)* illustrates the direct relationship between airway resistance (*R*aw) and lung volumes *(FRCpleth + VT)*. In addition, it offers an insight into the dynamics of the volume-dependency of airway resistance over the complete course of a representative normal breath (VT).

With reference to Figure 4, the left part of the chart outlines the resistance scale in which it is possible to detect the measured value of effective or total airway resistance (*R*eff or *R*tot). This is displayed using a horizontal dashed line linked to the Y axis. The green area outlines the normal predicted range of airway resistance.

Note: *In terms of physiology: The airway resistance (Y axis) is specific to the central components of the respiratory tract.*

The lower part of Figure 4 summarizes measured lung capacities and volumes on the X axis using a bar diagram. In addition, a predicted value bar below allows the measured parameters *(TLC, IC, FRCpleth, ERV and RV)* to be referenced against normative data. The importance of the FRCpleth parameter is highlighted by means of a vertical dashed line.

Note: *In terms of physiology: The X axis components of the R-V graph exclusively depend on the peripheral characteristics of the respiratory tract.*

The components of the R-V graph *(continued)*

The gray oval field combines the predicted ranges of *Raw* and FRCpleth. The circumference of the grey oval represents lower and upper limits of the normal ranges.

The bar diagram to the right of the R-V graph *(Figure 4)* displays the variability of measured airway resistance during the tidal breaths. A higher degree of obstruction is normally associated with a greater variance of airway resistance demonstrated by a longer bar diagram. The numerical value next to this bar outlines the difference between mean inspiratory and mean expiratory resistance across the tidal breath.

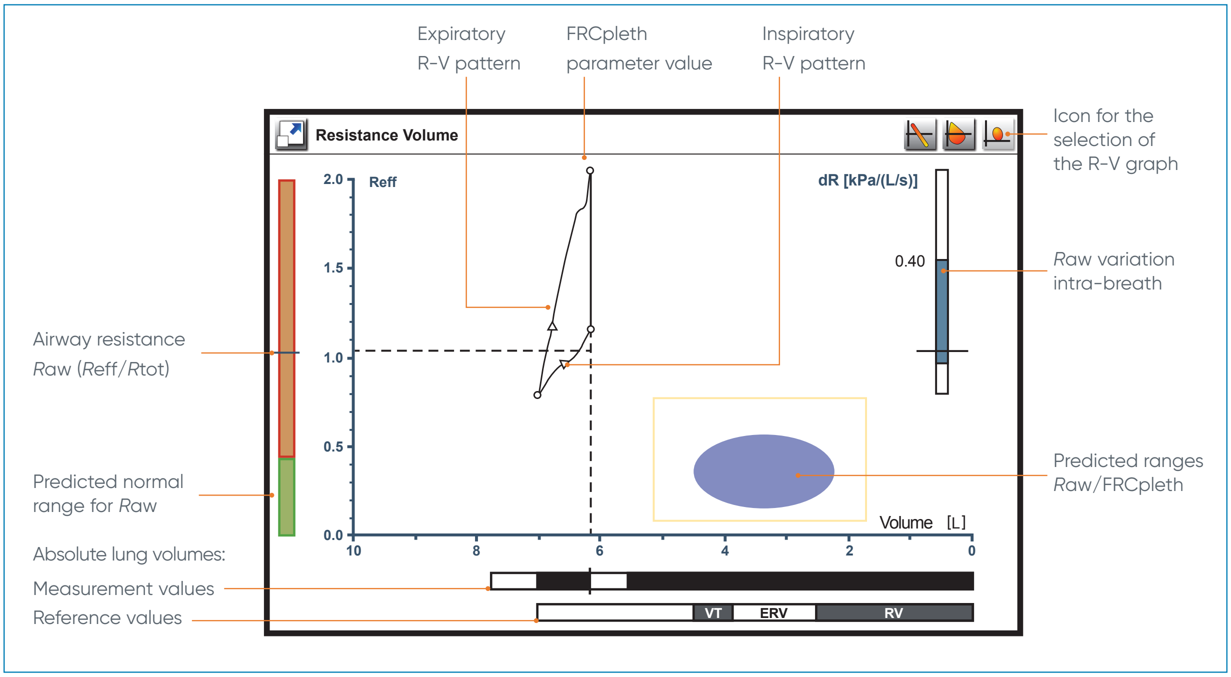

Figure 4: Description of the individual components of the R-V graph.

- Y axis: Resistance scale with predicted normal range
- X axis: Absolute volumes, measured and predicted
- Right: Intra-breath variation of *Raw*
- Center: R-V loop and predicted ranges of *Raw* and FRCpleth

R-V loop in detail

The R-V loop (resistance-volume loop) outlined in Figure 4 is detailed in Figure 5. The R-V loop trace utilizes markers *(triangles, circles)* that help characterize and identify the subcomponents of the R-V loop between the inspiratory and expiratory cycle. These markers allow quantitative evaluation of breathing dynamics during the breathing cycle and measure changes that occur due to dysfunction.

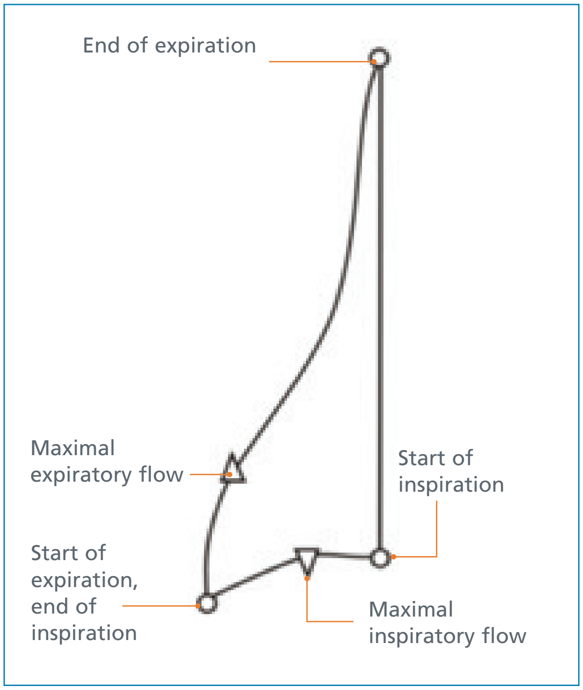

Figure 5: Markers on the R-V loop indicate key characteristic points within the breathing cycle.

The triangles (△) indicate the flow dependency of airway resistance. Within the breathing cycle, the values of airway resistance are marked at the points where the maximal inspiratory and expiratory flow occur.

Note: *Flow-dependency (flow type), i.e., the increase of resistance at maximal flow within the tidal breath is usually caused by the large central airways.*

Conversely, the circles (O) indicate the values of airway resistance at the zero flow phases:

- At the start of inspiration.
- At the transition from inspiration to expiration.
- At the end of expiration.

If the resistance of the airways at the start of the expiration differs largely between the airway resistance at the end of expiration, a volume-dependent component within airway resistance can be concluded.

Note: *The volume dependency of airway resistance (volume type) is usually caused within the lung's elastic recoil properties mediated by changes in peripheral lung parenchyma affecting the forces around the peripheral airways as well as reducing airway caliber, causing peripheral obstruction and inhomogeneity within the airway itself.*

Comparison of a conventional report and the R-V graph in a pre-post assessment

The R-V graph is particularly informative within pre- and post-assessments using a bronchodilator, as it clearly demonstrates the differentiated response to the bronchodilator within the bronchial system.

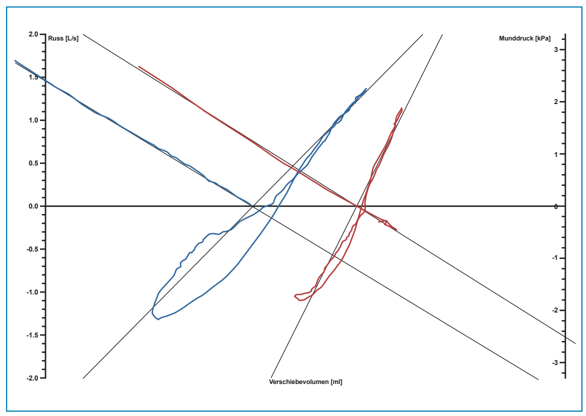

Figure 6a: Conventional graphic report of the s*R*aw breathing loops and FRC occlusion pressure curves of a pre-post assessment. Pre-measurement is displayed in blue, and post-measurement is displayed in red.

Figure 6a shows a common graphic report using a bronchodilator by means of the s*R*aw breathing loops and FRC occlusion pressure curves with the pre-measurements *(blue)* compared with the post measurements *(red)*. Looking at the graph, it is hard to see how much reduction in airway resistance may have occurred and also how much change may have occurred in lung volumes in relation to their predicted values.

Comparison of a conventional report and the R-V graph in a pre-post assessment *(continued)*

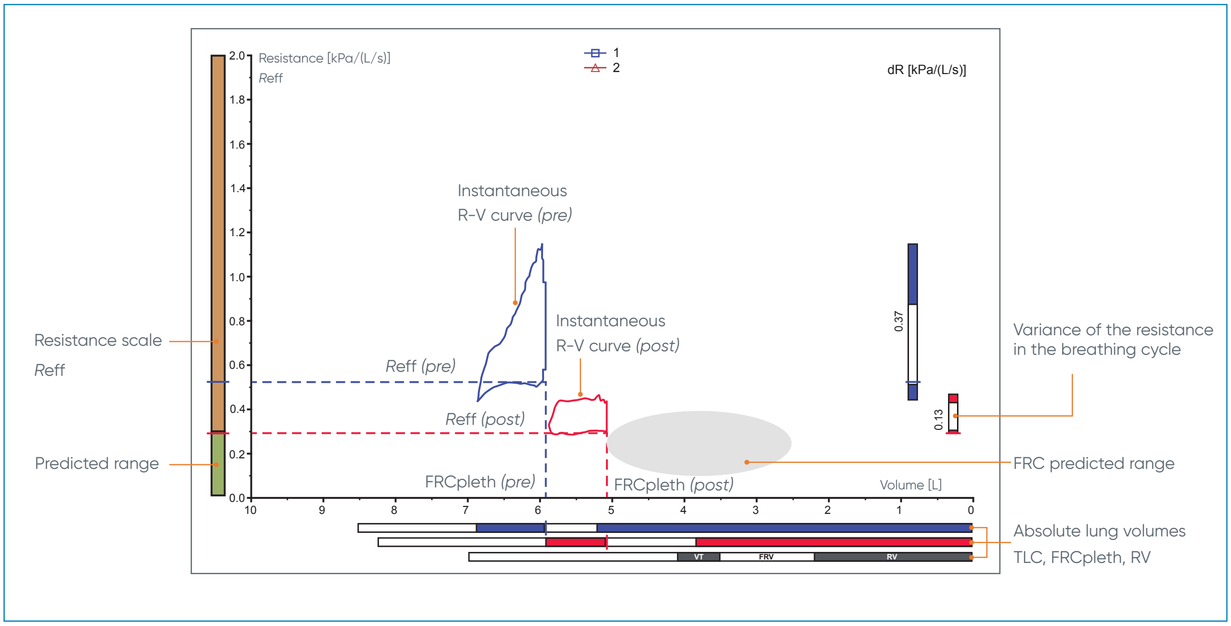

Figure 6b: The R-V graph of the bronchodilation from Figure 6a: The pre-measurement is shown in blue, and the post-measurement is shown in red. At a glance, it is possible to deduce clear information regarding the most important clinical issues with changes in resistance and post-bronchodilator volumes. Significant reductions in the post-measurement have occurred where *Reff* is within normal limits, and FRCpleth is now just above the normal range. The intra-breath variation of *Reff* is significantly reduced. Residual volume (RV) is reduced, but it still remains increased above normal limits.

The same bronchodilation examination displayed using R-V graph *(Figure 6b)* clearly outlines that the airway resistance (*Reff*) is within the predicted range in the post measurement as it falls within the normal *(green)* range of the vertical resistance scale *(left)*. The FRCpleth is reduced falling closer to the gray FRC predicted normal range in the post measurement. It is therefore clear to observe increases in the inspiratory capacity (IC) post-bronchodilator.

The X axis of the R-V graph summarizes absolute volumes of the pre- and post-measurements in comparison to their predicted values *(gray bar)*. Even though the degree of hyperinflation is reduced, visible in a reduction in residual volume (RV) and RV/TLC, these hyperinflation parameters are still significantly above predicted values when compared to the gray reference bar *(Figure 6b)*.

The chart clearly shows that the R-V curve *(red)* has moved downwards and to the right compared to the pre-measurement *(blue)*. Due to the effects of bronchodilation, the patient not only benefits from a reduction of the airway resistance, but the patient also benefits from a decrease of hyperinflation.

The variance of resistance (dR) in the post-measurement displayed in the right part of the report has fallen significantly.

The R-V graph allows for a fast and comprehensive diagnosis by merely evaluating the vertical and horizontal position of the R-V loop compared to predicted ranges for airway resistance and static lung volumes. The full potential of the R-V graph becomes clear when performing pre- and post-measurements. Here, the R-V graph explicitly displays the complexity and diversity of the bronchial reaction to a bronchodilator.

Conclusion

The R-V graph illustrates clearly the relationship between airway resistance and lung volume, not only in single measurements but also after bronchodilation *(Figure 7)*.

In addition, it offers an insight into the dynamics of airway resistance during the complete breathing cycle of spontaneous tidal breathing.

The possible conclusions with regard to the flow- and volume-dependency of the airway resistance are expected to be helpful in providing a more detailed classification and phenotyping of obstruction.

Furthermore, abnormal changes in the relationship between airway resistance and lung volume are clearly and definitively illustrated.

The R-V graph identifies changes in the airway resistance *(Y axis)* as specific to the central components and changes in lung volumes exclusively depending on the peripheral characteristics of the respiratory tract.

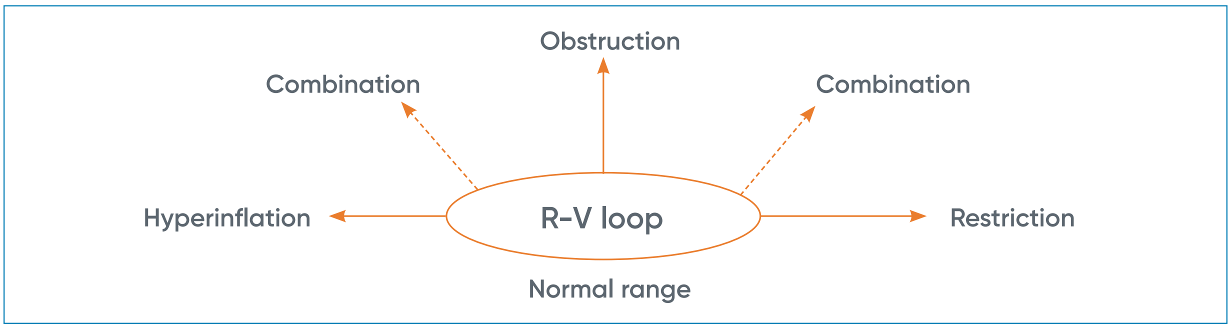

Figure 7: The arrows show the moving direction of the R-V loop according to the disease pattern.

Caution: *Generally, the R-V graph can be considered a simplified and clinically oriented summary of the whole body plethysmography measurement results, which illustrate the direct relationship between airway resistance and lung volume.*

Appendix

List of exclusive whole body plethysmography parameters

sRaw	kPa·s/cmH$_2$O·s	Common term for specific airway resistance

Note: *In various areas, the term sRaw is used as a synonym for sRcenter or sRmid. It is recommended to replace both approximations by sReff with the advantage that the latter has lower variability.*

sReff	kPa·s/cmH$_2$O·s	Effective specific airway resistance
sRtot	kPa·s/cmH$_2$O·s	Total specific airway resistance
Raw	kPa·s·L^{-1}/cmH$_2$O·s·L^{-1}	Common term for airway resistance

Note: *In various areas, the term Raw is used as a synonym for Rcenter or Rmid. It is recommended to replace both approximations by Reff with the advantage that the latter has lower variability.*

Reff	kPa·s·L^{-1}/cmH$_2$O·s·L^{-1}	Effective specific airway resistance
Rtot	kPa·s·L^{-1}/cmH$_2$O·s·L^{-1}	Total specific airway resistance
FRCpleth	L	Functional residual capacity
ITGV	L	Intrathoracic lung volume, synonym for FRCpleth
RV	L	Residual volume
TLC	L	Total lung capacity
RV/TLC	%	Fraction of RV in TLC

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GLOBAL HEADQUARTERS

Vyaire Medical, Inc.
26125 North Riverwoods Blvd
Mettawa, IL 60045
USA

Vyaire Medical GmbH
Leibnizstrasse 7
97204 Hoechberg
Germany