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## CHAPTER 24

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# Lung Mechanics Using Plethysmography and Spirometry

Elizabeth A. Rozanski • Andrew M. Hoffman

### *Background Physiology and Definition*

The goal of pulmonary function testing (PFT) is to provide an objective evaluation of the efficiency of the respiratory system to move air (ventilate) and exchange gases. Historically, in veterinary medicine, assessment of these two main features of the respiratory system has been subjective, largely based on clinical examination. Recently, arterial blood gas analysis, end-tidal CO<sub>2</sub> analysis, and pulse oximetry have become popular as measures of gas exchange and ventilation, but they do not provide a measure of lung mechanics (i.e., the amount of work required by the animal to maintain those blood gases or saturation). Hence the weakness in veterinary pulmonology is in the area of ventilation and lung mechanics, which constitute half of the picture.

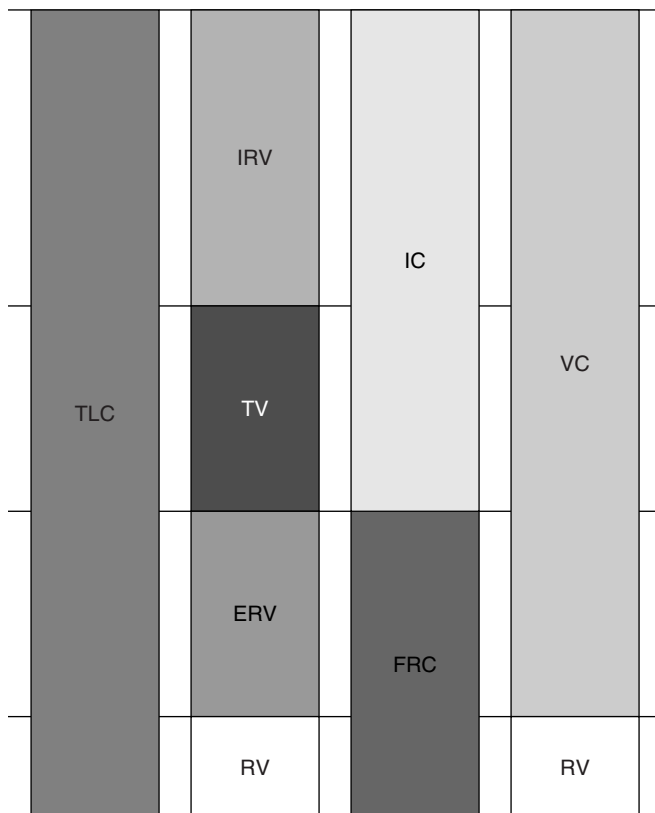
The first lung function tests were described over 150 years ago by Hutchinson, who described a method of measuring vital capacity.<sup>1</sup> Since that time, measurement of lung volume has become routine in both the physiology laboratory and the physician's office. PFT is routinely used in human medicine to provide an objective assessment of pulmonary function and a method for judging response to therapy. In veterinary medicine, PFT is most widely used to assess horses presenting with cough or exercise intolerance.<sup>2</sup> In small animal practice, PFT has been largely used in university settings.<sup>3-6</sup> PFT that has been described in small animal practice includes spirometry and tidal breathing flow-volume loop analysis, plethysmography, and measurement of compliance and resistance.<sup>3-6</sup> This chapter discusses the advantages and limitations of spirometry and plethysmography. Both techniques are currently available and have value for case management, particularly in critical care settings.

## Lung Volume Testing

Measurement of lung volumes (Figure 24-1) leads to a better understanding of pathophysiology, especially in the dyspneic patient. There are two major lung volume categories: dynamic lung volumes, including volumes that are displaced with breathing, and static lung volumes, which include gas trapped in the chest.

The dynamic lung volumes include tidal volume (TV), inspiratory reserve volume (IRV), expiratory reserve volume (ERV), and vital capacity (VC). The TV is the amount of air in an average breath at rest, usually 10 to 20 ml/kg in small animals. Functional residual capacity (FRC) is the amount of air remaining in the lungs after tidal expiration. IRV is the amount of air that can be inspired in excess of the normal tidal breath, whereas ERV is the amount of air that can be exhaled in excess of the normal tidal expiration. Residual volume (RV) is the air remaining in the lungs after ERV.

Vital capacity (VC) refers to the sum of ERV, TV, and IRV. Total lung capacity (TLC) is the sum of VC and residual volume (RV) and includes both static (RV) and dynamic (VC) lung volumes. Static volumes include the



**Figure 24-1.** Lung volumes are displayed graphically. Lung volumes include tidal volume (TV), inspiratory reserve volume (IRV), expiratory reserve volume (ERV), vital capacity (VC), total lung capacity (TLC), residual volume (RV), and functional residual capacity (FRC).

FRC and the RV. ERV is a dynamic volume that represents the difference between FRC and RV.

Dynamic lung volume measurements are typically measured with a device called a spirometer, a simple instrument that is calibrated to measure volumes. Historically, spirometers have used a water-sealed chamber system, although today many spirometers are electronic. Hand-held spirometers are also available and are used to some extent in evaluating lung volume in dogs and cats. The spirometer is capable of accurately measuring tidal volume and minute ventilation in individual patients (Figure 24-2). It may be attached to an airtight face mask or connected to an endotracheal tube. In addition, a spirometer may be used to accurately measure the volume of air delivered to a patient by a mechanical ventilator. In ventilated patients, large discrepancies may exist between the calculated tidal volume and the actual delivered tidal volume due to the compliance of the ventilatory circuit and its relation to the size of the patient. Whereas the spirometer is not widely used as a pulmonary function tool, it is commonly used in the intensive care unit to better assess ventilated patients and animals with potential hypoventilation.

Static lung volume (FRC and VC) measurement requires a different technique.<sup>1,7</sup> Most commonly, an inert gas dilution method is used; however, plethysmography is considered the gold standard. Gas dilution methodology requires the patient to breathe a known concentration of helium. Helium is relatively insoluble in blood, and over time the concentrations in the lung and the re-breathing device will equilibrate and reach a steady state. Using the equation:

$$C_1 \times V_1 = C_2 \times (V_1 + V_2)$$



**Figure 24-2.** A hand-held spirometer may be used to measure tidal volume and minute ventilation in an awake patient using a face mask.

where  $C$  equals the concentration of helium and  $V$  equals volume, solving for  $V_2$  will result in the determination of FRC:

$$V_2 = V_1 (C_1 - C_2) / C_2$$

The starting volume ( $V_1$ ) and starting concentration of helium ( $C_1$ ) must be known, and steady state measurements are required for accurate calculations. However, in individuals with air trapping, the FRC measured by plethysmography is greater and more accurate than that measured by helium dilution.

Body plethysmography is a very effective research tool in small animals, but as currently performed requires anesthesia.<sup>8</sup> The technique is based on Boyle's law, which states that there is a constant relationship between pressure ( $P$ ) and volume ( $V$ ) at a constant temperature, or mathematically,  $P_1 \times V_1 = P_2 \times V_2$ . Standard methodology used in plethysmography designed for human use typically includes an airtight box (the plethysmograph) in which the subject sits and breathes through a mouthpiece. The mouthpiece contains a shutter that may be opened and closed electronically. The subject is asked to breathe against the closed shutter at end-expiratory lung volume. Changes in the pressure measured at the mouth (reflecting alveolar pressure) and the changes in pressure in the box (reflecting thoracic gas volume) are recorded. FRC is then calculated as follows:

$$\frac{\Delta V}{\Delta P} \times (P_B - P_{H_2O}) = FRC$$

where  $\Delta V$  = change in volume,  $\Delta P$  = change in pressure,  $P_B$  = barometric pressure, and  $P_{H_2O}$  = water vapor pressure. In practice, the use of plethysmography requires several assumptions.<sup>7</sup> First, we assume that there is no flow during respiratory efforts against a closed airway, hence FRC is a static lung volume. This assumption is important in validating that the mouth pressure (airway opening pressure,  $P_{ao}$ ) is equivalent to alveolar pressure ( $P_{alv}$ ). Theoretically, airflow could occur within the upper airways (shunting) and result in underestimation of alveolar pressure and thus the overestimation of FRC. Practically this has not been a problem except in individuals with significant lower airway obstruction. The second assumption is that changes in pressure are uniform across the lung (i.e.,  $P_{ao} = P_{alv}$ ). If pressure changes were not uniform (e.g., in patients with air trapping) this would, in theory, result in measurement of a lower FRC. The final assumption is that air in the gastrointestinal tract is either insignificant or not compressed during occlusion, which is generally true. Despite the need to make these assumptions, there is no question that plethysmographic measurements can be accurately made in small animals under anesthesia in special cases.

In the future, a more user-friendly method will likely employ steady state helium dilution and a computer for rapid results. Finally, FRC can also be computed from CT scans of the chest, but these measurements require 3-D reconstructions and include a tissue component that overestimates FRC.

## Barometric Plethysmography for Measurement of Spirometric Indices in Normal Animals

Barometric whole-body plethysmography (BWBP) is a noninvasive method of measuring pulmonary function that has recently been validated in cats.<sup>9</sup> The origin of this method dates back to studies of Neergard (1926– and later, Jaeger (1964), Ingram (1966), and McLead (1971)—that describe marked discrepancies in volume displacement measured at the body surface versus the airway opening at the mouth or nose.<sup>10–13</sup> The difference in volume displacement measured by spirometry (mouth) and plethysmography (body surface) relates to both static and dynamic characteristics of the lung, including lung volume (TV and FRC), resistance to airflow (lung resistance,  $R_L$ ), the compressibility of thoracic gas, and breathing frequency.<sup>11</sup>

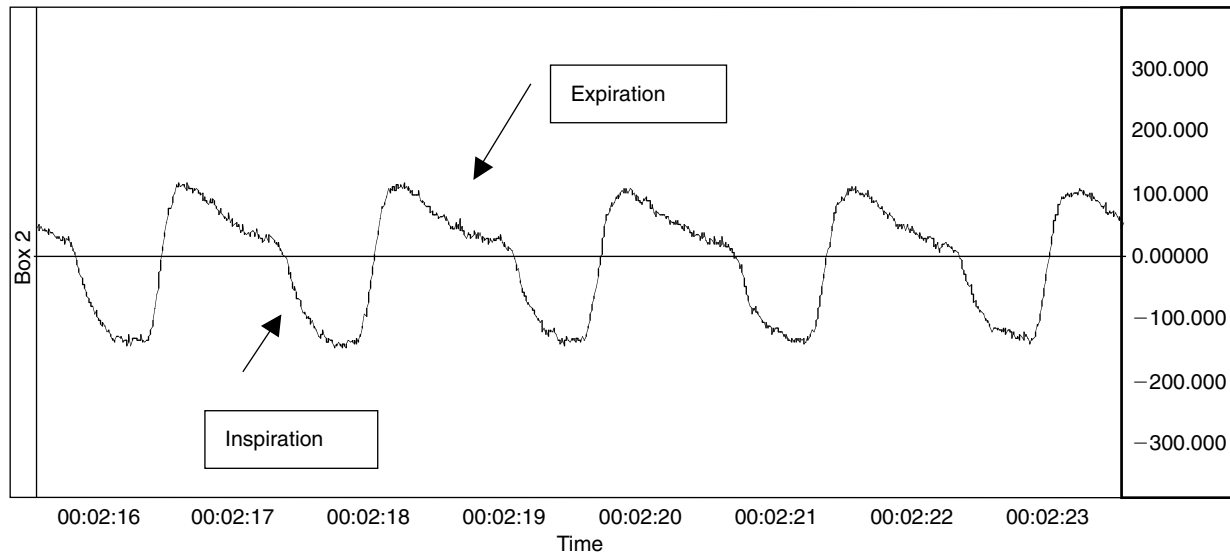
For example, tidal volume measured by plethysmography (volume displacement of the chest and abdomen) is greater than that measured by spirometry (true volume displacement at the mouth) in the presence of:

- Increased lung volume
- Increased  $R_L$  as gas behind an obstruction is compressed; as lung resistance increases, the plethysmography and spirometry difference is increased
- Decreased barometric pressure (i.e., high altitude associated with decreased barometric pressure and increased compressibility of gas)
- Increased breathing frequency, which increases the phase lag in the face of gas compression

Barometric whole-body plethysmography (BWBP) is based on the same concept, except that the changes are measured as a net effect during tidal breathing rather than compared as individual signals. In animals, similar phase and magnitude shift was found using double chamber plethysmography.<sup>14</sup> Later this observation was extended to single chamber plethysmography as well.<sup>15,16</sup> BWBP is performed by placing the patient within a single chamber plethysmograph (Figure 24-3).



**Figure 24-3.** Barometric whole-body plethysmography is performed by placing a cat within a plethysmograph. Note that the cat is free to move about and appears to be resting comfortably.



**Figure 24-4.** Barometric whole-body plethysmography signal from a normal cat. The inspiratory and expiratory phases are indicated.

The plethysmograph chamber is airtight, except that it is ventilated with a known bias flow, and a single-screen pneumotachograph with a known resistance is mounted on one wall allowing for a controlled leak of air. A differential pressure transducer sensing changes within the chamber is connected to a preamplifier and a pulmonary function computer. The animal is able to move around the chamber at will.

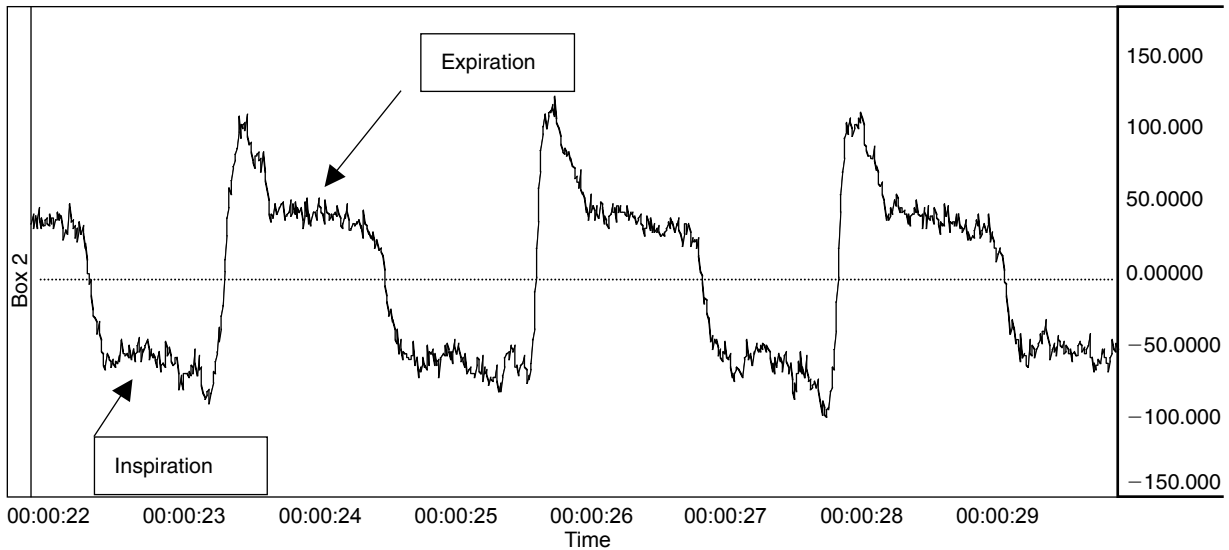
The breathing pattern is assessed by analysis of the box-pressure signals that vary during breathing. The signals associated with normal unobstructed breathing appear graphically similar to flow signals produced by conventional pneumotachography (Figure 24-4). These signals are produced as the net result of thoracic and nasal airflow causing pressure changes within the plethysmograph. Although these signals are always equal and opposite, warming of the air causes the thoracic volume change to slightly exceed the nasal volume change. Therefore, the net change in chamber pressure is the difference between thoracic and nasal flow. The normal BWBP signal is a measure of the normal difference in lung volume in the chest compared with that at the mouth/nose during a breath. This is in contrast to spirometry with a pneumotachograph that measures flow through the upper airway (nose and mouth).

Baseline values of standard respiratory parameters (e.g., tidal volume and respiratory rate) obtained in healthy cats were similar to those reported in awake, untrained cats during analysis of tidal breathing flow-volume loops acquired with a face mask and an associated pneumotachograph.<sup>5</sup> Cats in particular are very tolerant of BWBP and seem to be very comfortable during testing. In fact, in the distressed cat, 100% oxygen may be used instead of conventional room air bias flow with-

out invalidating the results and with a substantial improvement in patient comfort.

### *Barometric Whole Body Plethysmography for Measurement of Airway Obstruction*

Barometric whole body plethysmography is also an effective method to evaluate patients with airway obstruction. Resistance causes gas expansion during inspiration and compression during expiration, thereby resulting in an increased difference between displacements of volume at the nose (mouth) and body surface. BWBP has been validated in rodents and cats as an alternative non-invasive method of assessing experimental bronchoconstriction.<sup>9,17</sup> During airway obstruction, the signal is created by increased resistance and gas compression in response to increasing airflow limitations and magnified due to discrepancies in thoracic and nasal volumes complicated by a phase lag. The increased pressure changes within the chamber result in the visual appearance of a changed signal (Figure 24-5). In conventional pulmonary function testing, lung resistance ( $R_L$ ) measurements are thought to reflect narrowing of the larger diameter airways. Using conventional techniques, pause and enhanced pause are two unitless variables that correlate with  $R_L$ . In a small group of cats with naturally occurring bronchoconstriction due to asthma, values of pause and enhanced pause were increased when compared with healthy cats; and importantly, these values decreased towards normal following therapy with a bronchodilator.<sup>18</sup> BWBP detects both upper and lower airway diseases be-



**Figure 24-5.** Barometric whole-body plethysmography signal from a cat with bronchoconstriction due to feline asthma. The inspiratory and expiratory phases are marked. Note the difference in signal appearance compared with Figure 24-4.

cause any site of airway obstruction will result in increased pressure changes associated with breathing.

### Barometric Whole Body Plethysmography for Testing Airway Reactivity

Airway reactivity or bronchoprovocation testing is performed in people and in horses in an attempt to detect airway disease (e.g., inflammatory airway disease or chronic obstructive pulmonary disease) earlier in its course. It is also used in individuals with intermittent signs, and to detect response to various treatments. Airway reactivity testing is not performed if bronchoconstriction is already present at initial examination. Classically, bronchoprovocation to test airway reactivity is performed until a set increase occurs from the baseline value of  $R_L$  (e.g., a doubling [ $R_{L200}$ ]) due to narrowing of the airway in response to an agent such as histamine or methacholine. As in naturally occurring bronchoconstriction, pause and enhanced pause have been shown in rodents to correlate with  $R_L$  and pleural pressure changes caused by aerosol bronchoprovocation challenges.<sup>19</sup> In cats exposed to the bronchoconstrictive agent carbachol by aerosol, pause and enhanced pause greatly increased during bronchoconstriction.<sup>9</sup> A recent report suggests that airway reactivity diminishes with advancing age in cats.

In small animal patients, airway reactivity has not been widely tested; however, as BWBP becomes more widely available, reactivity testing may become more widespread, particularly in animals with intermittent signs or those in which other diagnostic tests do not elucidate the underlying disease.

### Barometric Whole Body Plethysmography for Monitoring Response to Therapy

BWBP is also useful for monitoring patients over time. The test is noninvasive and well tolerated by most small animal patients. Commonly, animals with airway disease require long-term medication and frequent veterinary examinations. BWBP, particularly coupled with reactivity testing, is a useful ancillary method to follow patient progress. BWBP may also be useful to assess the success of airway surgeries (e.g., for brachycephalic airway syndrome or laryngeal paralysis), as well as for immediate assessment of the effect of bronchodilator therapy.<sup>6,17,18</sup>

### Indications

Spirometry is indicated to assess tidal volume in patients receiving mechanical ventilation and to assess the adequacy of spontaneous respiratory efforts in animals with lower motor neuron disease, those being weaned from neuromuscular blocking agents, or those recovering from anesthesia.

Barometric whole-body plethysmography is useful to assess a patient with potential airway disease and then to assess the response to therapeutic intervention. Particular indications for cats include (1) asthma or suspected asthma, (2) following therapy for asthma, (3) those animals with intermittent poorly localizing signs of respiratory disease, and (4) suspected fixed airway obstructions. In dogs, specific indications include chronic bronchitis or collapsing trachea. Because some dogs are prone to panting when confined within a plethysmograph, it may be impossible to get adequate measurements. Light sedation



may be used, but may result in bronchodilation. BWBP may also be used in exotic pets such as birds, small mammals, and even pot-bellied pigs.

## Contraindications

There are no specific patient contraindications to spirometry or plethysmography. Tachypnea or panting at low tidal volumes will invalidate plethysmography results. Animals that are clearly in respiratory distress and appear to have extra-airway sources of disease (e.g., pleural effusion) will not benefit from lung function testing, except if it is needed to exclude concurrent airway obstruction.

## Instrumentation and Technique

Hand-held spirometers are available from a number of sources. Pulmonary function computers are less widely available for veterinary use. Buxco Electronics\* has marketed the most widely used software and computers designed for pulmonary function testing in clinical small animal medicine, as well as in research settings. A complete discussion of pulmonary function equipment is beyond the scope of this article; however, an understanding of commonly required equipment may be helpful.

In general, pulmonary function equipment and software is designed to calculate pressure, volume, and flow changes. These changes reflect the work the pulmonary system is doing in order to maintain adequate oxygenation and ventilation. For classic pulmonary function testing involving measurement of static or dynamic compliance ( $C_{stat}$  or  $C_{dyn}$ ) and lung resistance ( $R_L$ ), measurements of flow and pressure are required. Flow (ml/sec) may be measured by a face mask and pneumotachograph and integrated to give volume (ml). Practically, because flow in the healthy patient is sinusoidal, computer-based calculations are much more accurate than hand measurements. Pressure measurements typically require placement of an esophageal balloon in the midthoracic esophagus to approximate transpulmonary pressure. The relationship of pressure to flow and volume during various points in the respiratory cycle is used to calculate the desired values. The units for  $C_{stat}$  or  $C_{dyn}$  are ml/cm  $H_2O$ ; and for  $R_L$ , cm  $H_2O/L/sec$ .

\*Buxco Electronics, Sharon, Conn.

In BWBP, different equipment is used. A plethysmograph is an airtight box, constructed of Plexiglas, that is ventilated with a bias flow of room air or 100% oxygen. The bias flow is recommended to prevent over-heating, which will diminish the signal, and also to prevent carbon dioxide retention in the chamber. A single screen pneumotachograph with a known resistance is attached to a corner wall. The pneumotachograph is calibrated before use. To limit the impact of minor barometric pressure changes, a differential pressure transducer is mounted on a neighboring wall with one port open to the chamber and the other port open to a reference chamber. The pressure transducer is connected to a pre-amplifier data acquisition card and then to the computer. The software program recognizes real-time pressure changes and records and stores data for later analysis. Parameters that are recorded by the computer include: peak inspiratory flow (PIF); peak expiratory flow (PEF); tidal volume (TV); end-inspiratory pause (EIP); end-expiratory pause (EEP); frequency (f); expiratory time ( $T_e$ ); inspiratory time ( $T_i$ ); relaxation time (RT, the time for box pressure to decay to 30% of total box pressure during expiration); pause ( $[(T_e/Rt)-1]$ ); and enhanced pause ( $PENH=(T_e/[0.3 \times RT]-1 \times PEF/[PIF \times 0.67])$ ).

During BWBP, the patient is placed in the chamber and allowed to relax during data collection. After baseline data collection, further testing may be pursued. Bronchoprovocation (airway reactivity) may be performed if baseline values are not abnormal, and therapeutic interventions (e.g., Beta-2 agonists) may be used if bronchoconstriction is present.

## Interpretation

Interpretation of spirometry is based on knowledge of a normal tidal volume for a particular patient and, in general, is defined as either adequate or inadequate. In the awake patient, application of a face mask may influence breathing pattern and possibly result in an increased tidal breath, so appreciation of hyperpnea is limited.

Interpretation of barometric whole-body plethysmography is based on comparison of results with known normal values. In cats, published normal values exist and are listed in Table 24-1, although it is likely prudent for the individual laboratory to create its own normal values.<sup>5,9</sup> As previously mentioned, airway reactivity was found to decline with age in healthy cats. No normal values for BWBP have yet been reported in dogs, per-

TABLE 24-1. Selected Barometric Whole Body Plethysmography (BWBP) Values ( $\pm$  SEM) and Values ( $\pm$  SD) Derived From Tidal-Breathing Flow-Volume Loop (TBFVL) Data for Normal Cats<sup>5,9</sup>

	$T_i$	$T_e$	TV	PEF	PIF	Rate
BWBP	470 $\pm$ 40	730 $\pm$ 100	35 $\pm$ 4	83 $\pm$ 12	109 $\pm$ 8	58 $\pm$ 8
TBFVL	716 $\pm$ 139	704 $\pm$ 133	58 $\pm$ 15	114 $\pm$ 29	111 $\pm$ 27	43 $\pm$ 7

$T_i$  = Inspiratory time in msec;  $T_e$  = expiratory time in msec; TV = tidal volume in ml; PEF = peak expiratory flow in ml/sec; PIF = peak inspiratory flow in ml/sec; Rate = respiratory rate in breaths/min. Note (see text) that flow measurements are not representative of the same signal.

haps due to their tendency to pant when confined. In particular, for animals with suspected bronchoconstriction, the values for pause and enhanced pause should be carefully evaluated. Cats with bronchoconstriction have increased values of pause and enhanced pause, as well as changes in signal characteristics (see Figures 24-4, and 24-5). Results may also be interpreted serially following a change in the patient's clinical condition or following a therapeutic intervention. Longitudinal data collection will also allow for long-term follow-up on individual patients, as well as on a variety of patient populations.

Barometric whole-body plethysmography represents an exciting area of pulmonary function testing in small animal patients. In particular, the utility of this form of testing includes its ability to test animals with respiratory distress and its completely noninvasive nature.

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## CHAPTER 25

# Interpretation of Blood Gas Measurements

Steve C. Haskins

**B**lood gas analysis is the measurement of partial pressures of carbon dioxide and oxygen in the blood. The partial pressure of carbon dioxide in arterial blood defines alveolar minute ventilation. End-tidal and venous blood carbon dioxide measurements, under many circumstances, can be used to estimate arterial carbon dioxide. The partial pressure of oxygen in arterial blood defines the ability of the lungs to oxygenate the blood. Hemoglobin saturation is directly related to the

partial pressure of oxygen and, under many circumstances, can be used to approximate the partial pressure of oxygen. The oxygen content of blood is highly dependent on hemoglobin concentration and is important to oxygen delivery. Mixed venous oxygen reflects the balance between oxygen delivery and oxygen consumption; it cannot be used to approximate arterial oxygen and is interpreted with an independent set of rules.