INTRODUCTION
The purpose of this document is to list, define and describe in detail the calculations required to compute the parameters available from the FloTrak Elite module with the Capnostat 5 sensor.

Principles of Operation – Flow is measured with a fixed orifice differential flow sensor. Airway and barometric pressure are measured with gauge and absolute pressure transducers, respectively. CO₂ is measured by a mainstream infrared absorption (IR) technique with the Capnostat 5 sensor.

DEFINITIONS
Averaging – Unless otherwise noted, all parameters are computed on a breath-by-breath basis. Some parameters are computed as a moving average over the last eight breaths. Note, that if a rate corresponding to less than eight breaths per minute of either a spontaneous or mechanical breath type occurs, only breaths in the last minute are used for that average.

Neonatal vs. Pediatric vs. Adult – The software distinguishes between the flow sensors and the CO₂/flow sensors and detects whether the connected sensor is an adult, adult/pediatric, pediatric or neonatal sensor. Once detected, the corresponding parameter set applies, i.e., neonatal then the neonatal parameter set applies. The parameter RSBI applies only to pediatric and adult subjects. Additionally, the software applies different correction factors to the flow measurement based upon which flow sensor is connected. These correction factors adjust the measured values in order to correct for differences in geometry and flow velocity profiles of each of the flow sensors. Refer to whitepaper “Flow Measurement with Respironics Flow Sensors”, OEM1101A for details.

Spontaneous vs. Mechanical Breath Discrimination – The pressure recognition threshold for differentiating “spontaneous” from ventilator-delivered breaths is applied on a breath-to-breath basis and can be adjusted by the user. To differentiate, the software compares the peak inspiratory pressure (PIP) to this threshold level which is the baseline pressure level (PEEP) plus a user-defined offset. If the PIP is greater than this threshold level it will be categorized as a mechanical breath. If the PIP is less than or equal to this threshold level, the breath is considered to be a “spontaneous” breath. The default value for the user-defined offset is 6 cm H₂O.

Breath Detection – Detection of start of inspiration and expiration is performed with a robust threshold method, which requires that minimum flows and volumes be attained. Different thresholds are used for neonatal, pediatric and adult flow sensors. Once flow crosses an initial level, a breath is suspected. If the measured volume for a suspect breath meets the minimum volume requirements for inspiration and expiration the breath has been officially detected. Minimum detectable volume thresholds are 1, 5 and 20 ml for the neonatal, pediatric and pediatric/adult flow sensors, respectively.

Deadbands – To minimize the effect of drift, flow measurement systems employ deadbands about the zero level. For the available flow only and CO₂/flow sensors, the flow deadband thresholds are approximately 0.2, 0.5, 2, and 2 L/min for the neonatal, pediatric, pediatric/adult and adult sensors respectively.

Parameter Abbreviations – For each displayed parameter, the abbreviation used is shown with each parameter definition.

Table 1 - Flow Only and Combined CO₂/Flow Sensors

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Part Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined CO₂/Flow</td>
<td></td>
</tr>
<tr>
<td>Adult Combined CO₂/Flow Sensor</td>
<td>(Catalog No. 6719-00)</td>
</tr>
<tr>
<td>Pediatric Combined CO₂/Flow Sensor</td>
<td>(Catalog No. 6716-00)</td>
</tr>
<tr>
<td>Neonatal Combined CO₂/Flow Sensor</td>
<td>(Catalog No. 6720-00)</td>
</tr>
<tr>
<td>Flow Only Sensors</td>
<td></td>
</tr>
<tr>
<td>Pediatric/Adult Flow Sensor</td>
<td>(Catalog No. 6717-00)</td>
</tr>
<tr>
<td>Neonatal Flow Sensor</td>
<td>(Catalog No. 6718-00)</td>
</tr>
</tbody>
</table>
The breathing cycle can be divided into three intervals:

- Inspiration
- Expiration
- Pause

The automatic determination of these reference points can be hindered by zero-point drift, coughing, swallowing and cardiogenic oscillations. A robust flow detection algorithm is used to minimize the sensitivity to these effects. The volume is computed from the flow samples using trapezoidal integration.

**VENTILATORY PERIOD ($T_{tot}$) (sec)** – The time from the beginning of inspiratory flow of one breath to the beginning of inspiratory flow for the next breath (total cycle time); the sum of inspiratory time and expiratory time; the reciprocal of ventilatory frequency.

**INSPIRATORY PHASE (inspiration)** – Portion of the ventilatory cycle from the beginning of inspiratory flow to the beginning of expiratory flow. Any inspiratory pause is included in the inspiratory phase.

**INSPIRATORY OR INSPIRED TIME ($T_i$) (in seconds)** – Duration of the inspiratory phase (the time from start of inspiration to end of inspiration).

**EXPIRATORY PHASE (expiration)** – Portion of the ventilatory cycle from the beginning of expiratory flow to the beginning of inspiratory flow.

**EXPIRATORY OR EXPIRED TIME ($T_e$) (in seconds)** – Duration of the expiratory phase (the time from start of expiration to end of expiration).

**FREQUENCY OR RESPIRATORY RATE ($T_{tot}$) (in breaths/min)** – Measured from the start of inspiration of breath $N$ to the start of inspiration of breath $N+1$ and computed as an eight breath moving average of $60/T_{tot}$ and updated breath-by-breath. Composite (all breaths), mechanical and spontaneous frequencies are all separately computed as an eight breath moving average.

**INSPIRATORY-EXPIRATORY RATIO (I:E)** – Calculated as the ratio of the inspiratory time (time between start and end of inspiration) and expiratory time (time between end of inspiration and start of next inspiration) using all breaths and updated on a breath by breath basis. The output of this ratio is displayed in the form of:

(a) $1 : x$ if the computed ratio is less than 1:1 and shown to one decimal place.
(b) $x : 1$ if the computed ratio is greater than 1:1 and shown to one decimal place.

**FLOW AND VOLUMES**

**PEAK EXPIRATORY FLOW (PEF) (in L/min)** – Maximum negative flow measured during the expiratory period of a breath.

**PEAK INSPIRATORY FLOW (PIF) (in L/min)** – Maximum positive flow measured during the inspiratory period of a breath.

**MINUTE VENTILATION (MV) (in L/min)** – The quantity of gas exhaled expressed as volume per minute, and is calculated by expressing the eight-breath moving average of expiratory volume in terms of volume per minute and updated every breath. Total minute ventilation is calculated using all breaths. Mechanical and spontaneous minute ventilations are separately calculated using only mechanical and spontaneous breaths, respectively and may not sum to the value shown for the total minute ventilation due to averaging over different time intervals.

**EXPIRATORY VOLUME ($V_T$) (in mL)** – Volume measured during the expiratory interval. Note breath by breath values, and 8 breath averages available for spontaneous, mechanical and total breaths.

**INSPIRATORY VOLUME ($V_i$) (in mL)** – Volume measured during the inspiratory interval. Note breath by breath values, and 8 breath averages available for spontaneous, mechanical and total breaths.
Rapid Shallow Breathing Index (RSBI) (in breaths/min/liter) is the respiratory rate divided by the average spontaneous tidal volume (26). It is calculated as an 8 breath average, and only if spontaneous breaths are detected, the spontaneous minute ventilation is greater than the mechanical minute ventilation and the respiratory rate of those breaths is less than 57 breaths/minute. (Available only if CO₂/flow adult and pediatric sensor and pediatric/adult flow sensor are detected.)

Auto-PEEP (Indicator) – This indicator is set whenever auto-PEEP is detected in the breath. Usually considered to exist when inspiration occurs and the expired flow has not reached zero (no Pause apparent) because insufficient time has elapsed to allow the lung to passively deflate (11,21). This determination is made using both the pressure level measured at the flow reversal between expiration and inspiration and the width of the expiratory pause interval. This pressure level is compared to the PEEP level and if it exceeds the PEEP level by greater than 1 cm H₂O or the expiratory pause interval is minimal (<= 20 ms) in duration then the existence of auto-PEEP is indicated to the user.

Plateau (Peak Static) Pressure (Pplat) (in cm H₂O) – The airway pressure during an inspiratory pause just before the start of expiration. It is the sum of end-expiratory central airway pressure (PEEP) and the pressure required to distend the thorax by the tidal volume (21). Pplat is measured at the end of inspiration under stop flow conditions by a transient occlusion or by a machine-imposed end-inspiratory pause. It decays to a plateau value over 0.3 to 2.0 seconds. The values for Pplat are generally 1 to 5 cm H₂O less than the pressure recorded at flow cessation. This parameter is only reported if a sufficient period of no flow exists. This parameter is calculated only when using adult and pediatric flow sensors.

P0.1 (in cm H₂O) The airway pressure at 100 msec after the start of inspiration, is an indication of respiratory drive. The parameter is only calculated if there is an initial negative dip in airway pressure at the start of inspiration. This parameter is calculated only when using adult and pediatric CO₂/flow sensors and the pediatric/adult flow only sensor.
PARAMETER CALCULATIONS

REPIRATORY MECHANICS

Dynamic Compliance ($C_{dyn}$) (mechanical) (in mL/cm H$_2$O) (least squares) – Traditionally, dynamic compliance has been calculated as the ratio of the change in volume to the change in pressure over inspiration (16) or specifically as the ratio of the maximum inspiratory volume over the difference between Pexp and Pinsp. (See Figure 1). A more robust estimator of dynamic compliance is computed by least squares fitting of the flow, volume and pressure raw waveform data to a simple model (see following page for details).

Static Compliance ($C_{st}$) (mechanical) (in mL/cm H$_2$O) – Calculated for mechanical breaths that have an inspiratory pause (i.e., value for plateau pressure can be determined). It is calculated as the ratio of the tidal volume at the beginning of the inspiratory hold (assumed to be at maximum inspiratory tidal volume) divided by the difference between the plateau pressure and PEEP.

Airway Resistance–Inspired ($R_{awi}$) (mechanical) (in cm H$_2$O/L/sec) (least squares) – Inspired airway resistance has been traditionally calculated as the ratio of driving pressure during expiration to the end inspiratory flow. The driving pressure is the difference between the end inspiratory pressure and the plateau pressure. This resistance represents the dynamic resistance to inspiratory airflow created by the breathing circuit, ET tube, and major airways of the lung. A robust estimator of inspiratory airway resistance is computed by least squares fitting of the flow, volume and pressure raw waveform data to a simple model.

Airway Resistance–Expired ($R_{awe}$) (mechanical) (in cm H$_2$O/L/sec) (least squares) – Expired airway resistance has been traditionally calculated as the ratio of driving pressure during expiration to the maximum expiratory flow. The driving pressure is the difference between the plateau pressure and pressure at the maximum expiratory flow (See note 1). A robust estimator of expiratory airway resistance is computed by least squares fitting of the flow, volume and pressure raw waveform data to a simple model.

Least-Squares resistance and compliance

The least squares fitting methods for calculating resistance and compliance were first described in the late 1960’s (24). Resistance and compliance values were computed based upon the measurement of patient airflow, volume and intraesophageal pressure. Some investigators have applied this methodology with airway pressure instead of intraesophageal pressure. Other investigators have applied this approach to more complicated models of the
respiratory system that included higher order terms and terms for inertance. Use of this modeling approach is common in the neonatal respiratory mechanics literature (19). The least squares fitting method assumes a specific model for the respiratory system and fits the waveform data to that model. It is applied during inspiration, expiration, and over the whole breath cycle. It uses all of the data points in the breath cycle and tends to be a more robust method than methods that rely on the difference between two points in the breathing cycle such as the Jonson (8) or Suter (20) methods for resistance. The lung is assumed to be a single compartment, linear model consisting of a compliance in a series with a resistance that can be mathematically expressed as:

\[ \Delta P_i = R \dot{V}_i + \frac{1}{C} V_i \]

where \( R \) is a resistive term, \( C \) a compliance term, \( P_i = \Delta P_i \), the \( i \)th pressure difference, \( V_i = \Delta V_i \), the \( i \)th volume sample, and \( \dot{V}_i \) \( i \)th flow sample. The pressure difference is the pressure relative to a baseline level. The PEEP of the prior breath is used as the baseline level. The PEEP of the prior breath is used as the baseline level. The \( \Delta P_i \) minimizes the sum of squares between the observed ‘pressure’, \( P_{\text{observed}} \), and the best fit curve, \( P_{\text{bestfit}} \).

\[ S = \Sigma (P_{\text{BestFit}} - P_{\text{Observed}})^2 \]

To ‘minimize’ the error between the best fit and observed pressures, the partial derivatives of \( S \) with respective to \( R \) and \( C \) are computed, set to zero and solved for \( R \) and \( C \). This results in expressions for \( R \) and \( C \) consisting of products of volume and flow, pressure and volume, and flow themselves.

\[ R = \frac{\Sigma V^2 \Sigma \dot{V}^2 - \Sigma PV \Sigma \dot{V} \dot{V}}{\Sigma \dot{V}^2 \Sigma V^2 - (\Sigma \dot{V}V)^2} \]

\[ C = \frac{\Sigma V^2}{\Sigma PV - R \Sigma \dot{V}V} \]

The summations of these products are accumulated throughout the inspiratory and expiratory portions of the breath from which dynamic compliance and resistance values are calculated. The determination of the dynamic compliance value is based upon the data samples for a complete breath from the beginning of inspiration to the end of expiration. The inspiratory and expiratory resistance values are based upon the data samples for the inspiratory and expiratory portions of the cycle, respectively. The adequacy of the ‘model’ can be visually assessed by substituting the values determined and plotting the data samples and best fit curve on the same axis. Figure 5 illustrates the fit for the whole breath. Higher order terms can be added to correct to the small difference between the model and the actual curve for the whole breath plot.

**Figure 5** - Pressure-Volume Curves - Data samples and least squares curve fit; Whole Breath.

**CAPNOGRAPHY**

Note: These parameters are calculated by the Capnostream 5 CO\(_2\) sensor and transmitted to the Flotrac Elite module.

**End Tidal CO\(_2\) (PetCO\(_2\))** (in mmHg, % or kPa – user selectable)

- Maximum \( \text{CO}_2 \) measured during the averaging period. Single breath, 10, and 20 second interval values are available and operator selectable. The value is calculated by performing an 80 ms moving average of the expiratory \( \text{CO}_2 \) samples and reporting the largest average value over the expiratory interval as the end-tidal value.

**Inspired CO\(_2\)** (in mmHg, % or kPa – user selectable)

- The minimum \( \text{CO}_2 \) value during the last 20 seconds. This value is reported only when greater than 3 mmHg of \( \text{CO}_2 \) is present for the last 20 seconds.

**Respiratory Rate** (in breaths/min)

- The respiratory rate based on the capnogram is calculated as described in the whitepaper titled “Respiratory Rate Measurement in Respironics CO\(_2\) Sensors”, OEM1013A. Note, the respiratory rate is not used if a flow sensor is connected since the value determined from the flow waveform is considered more reliable.
VOLUMETRIC CAPNOGRAPHY

The CO₂ versus volume plot (Figure 7), a graphical presentation of measurements such as CO₂ elimination, and airway and physiologic dead space, is also known as the volumetric capnogram (Figure 8).

Volume of CO₂/Minute (\(\dot{V}\)CO₂-STPD) (in mL/min) –
Average of the net CO₂ volume/breath normalized to a minute and expressed in standard temperature and pressure, dry conditions. The net CO₂ volume per breath is calculated by summing the product of % CO₂ and volume samples over the whole breath from inspiration to the end of expiration so that the inspired/rebreathed CO₂ volume is subtracted from the expired CO₂ volume. (See Figure 6). This volume is effectively the area between the expiratory and inspiratory portions of the CO₂ volume curve, (See Figure 7). Different averaging intervals for \(\dot{V}\)CO₂ are available and should be used depending upon the clinical applications. The available range of averaging intervals include 1 breath, 8 breaths, 1 minute, 3 minutes, 5 minutes and 10 minutes. The 1, 3 and 10 minute averaging intervals use 15 second updates. Although often incorrectly referred to as CO₂ production, this value represents the net volume of CO₂ exhaled per minute (i.e. eliminated) rather than the volume of CO₂ produced by metabolism.

Mixed Expired CO₂ (PeCO₂ or FeCO₂) (in mmHg, % or kPa – user selectable) – Volume weighted 3 minute average CO₂ calculated by dividing the volume of CO₂ by the total expired volume for the same interval.
Alveolar (Effective) Minute Ventilaton (MV_{alv}) (in L/min) – Computed using the alveolar (effective) tidal volume normalized to a minute and reported as an 8 breath average. Note separate values are calculated for spontaneous, mechanical and all breaths.

For more information on volumetric capnography, please refer to the white paper titled “Volumetric Capnography – The Next Advance in CO_{2} Monitoring”, OEM1108A.

CARDIAC OUTPUT
Note: These parameters are only available with the cardiac output measurement option.

A variation on the traditional rebreathing methods, the differential Fick partial re-breathing technique was first described by Gedeon (28). In partial re-breathing an alternative form of the Fick equation is used. That is the change in $\dot{V}_{CO_{2}}$ and the change in end-tidal $CO_{2}$ in response to a change in ventilation is used in the Fick calculation. This differential form of the Fick equation can be simply derived and complete rebreathing simply shown to be a special case.

$$\dot{Q}_{PCBF} = \frac{\Delta \dot{V}_{CO_{2}}}{\Delta CaCO_{2}}$$

where $\Delta \dot{V}_{CO_{2}}$ and $\Delta CaCO_{2}$ are the change in carbon dioxide elimination of $CO_{2}$ in ml/min, and change in blood content in ml CO_{2} /ml blood between the baseline and rebreathing periods, respectively. This estimate considers only that part of the cardiac output which participates in gas exchange, i.e., the non-shunted blood flow or the pulmonary capillary blood flow (PCBF). By estimating the amount of blood flow bypassing the lung (shunt flow) and adding it to the PCBF, cardiac output may be determined. This method as implemented in the Flotrak Elite module uses a CO_{2}/flow sensor in conjunction with an adjustable deadspace breathing loop with a pneumatically controlled valve assembly.

Details on the rebreathing valve may be found in the whitepaper “Development and Testing of a Valve for Partial Rebreathing Cardiac Output Measurement” OEM1010A. Additional algorithmic details made be found in Jaffe (1999) (29).

Pulmonary Capillary Blood Flow (PCBF) (in L/min) – The measurement of blood flow involved in gas exchange as calculated using the partial rebreathing method.

Cardiac Output (CO) (in L/min) – Cardiac output is the measurement of blood flow pumped by the heart. It is calculated by correcting the PCBF for the amount of shunt.

Airway (Anatomic) Dead Space (Ineffective Tidal Volume) (V_{daw}) (in mL) — The volume of the conducting airways at the ‘midpoint’ of the transition from dead space to alveolar gas. The functional definition of airway dead space, also known as Fowler’s dead space (7), originally implemented for nitrogen, is computed using the extrapolated phase III slope. The line defined by this extrapolation and the value at which volumes of CO_{2} represented by areas p and q are equal determine the airway deadspace. The slope of phase III is computed by linear regression of the points bounded by 30% and 70% of expired CO_{2} volume (1,2,10,23).

Alveolar Tidal Volume (Effective Tidal Volume) (V_{t_{alv}}) (in mL) — The volume of the breath which reaches the alveoli. It is calculated as the difference between the expired tidal volume and airway dead space and reported as an 8 breath average. Note separate values are calculated for spontaneous, mechanical and all breaths.

For more information on volumetric capnography, please refer to the white paper titled “Volumetric Capnography – The Next Advance in CO_{2} Monitoring”, OEM1108A.

Figure 8 - Top: Components of volumetric capnogram (CO_{2} / Volume Plot). Bottom: Deadspaces shown graphically. Airway dead space as illustrated by Triangles p and q are of equal area. Area X is the volume of CO_{2} in the expired breath, while areas Z and Y are from airway and alveolar deadspace (V_{daw} and V_{dalv}). Because it does not contribute to CO_{2} elimination, all deadspace is wasted ventilation. (Adapted from Arnold [27] and Fletcher [6]).
Cardiac Index (CI) (in L/min/m²) – Cardiac Index is cardiac output normalized by body surface area. Body surface area is computed using the patient’s height and weight.

Stroke Volume (SV) (in mL) – Volume of blood pumped by the heart each beat or stroke. Typical value is 70 mL. Stroke Volume is cardiac output divided by average pulse rate (determined from the pulse oximeter and provided to the FloTrak Elite module by the host system).

Stroke Volume Index (SVI) (in mL/m²) – Stroke volume index is calculated as stroke volume normalized by the body surface area. Typical value is 40.

REFERENCE


