Maneuver-Free Determination of Compliance and Resistance in Ventilated ARDS Patients*

Josef Guttmann, Ph.D.; Luc Eberhard, Eng.; Gunther Wolff, M.D.; Wolfgang Bertschmann, M.D.; Julius Zeravik, M.D.; and Michael Adolph, M.D.

At present, most methods of lung mechanics analysis do not take nonlinearities of compliance and resistance into account. Nevertheless, nonlinearity of compliance is an inherent property of the respiratory system in ARDS and nonlinearity of resistance is an inherent property of the endotracheal tube. Herein we describe a computer-assisted multipoint method (LOOP) for breath-by-breath calculation of total respiratory system compliance (Ctrs) and total respiratory system resistance (Rtrs). Unlike our previously published method, LOOP excludes nonlinearities of compliance and resistance by confining the data used from the P/V/V loop to sequences with constant flow in inspiration and with steadily decreasing flow in expiration. LOOP was applied to five patients ventilated after open heart surgery (HEART group) and 12 patients ventilated for ARDS (ARDS group). The compliance results from LOOP were compared with the semistatic reference values corrected for intrinsic PEEP (CsST,IP). In the ARDS patients the compliance values from LOOP (46 ml/mbar) corresponded well with the semistatic compliance (CsST,IP = 42 ml/mbar). Despite the fact that there is no reference method for resistance known to date, we also determined the semistatic resistance (RsST) at end-inspiratory pause. The resistance values determined with LOOP were 8.5 mbar/L/s (RsST = 7.3 mbar/L/s) in the HEART group and 11.1 mbar/L/s (RsST = 8.6 mbar/L/s) in the ARDS group. LOOP gives a good correspondence between the linear RC model and the measured data in ARDS patients. In conclusion, LOOP requires neither an end-inspiratory pause (EIP) nor additional determination of intrinsic PEEP and gives Ctrs, automatically corrected for IPEEP, as well as Rtrs breath by breath at the bedside. (Chest 1992; 102:1235-42)

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n patients mechanically ventilated for severe acute respiratory failure, such as adult respiratory distress syndrome (ARDS), pulmonary state and course are assessed by evaluating gas exchange, pulmonary circulation, distensibility (compliance), and flow resistance. The most commonly used methods for determining “semistatic” compliance (CsST) and resistance (RsST) are methods that require a zero flow phase to be introduced at the end of inspiration (end-inspiratory pause; EIP) and at the end of expiration. Since calculation of CsST and of RsST uses the pressure difference between two defined points within the total breath, they are referred to as two-point methods. If expiration is incomplete, flow at the end of expiration is not zero and—to assess compliance—additionally intrinsic PEEP (IPEEP) must be measured with a special maneuver. More than two zero flow phases are realized with the “interrupter” method, which is a multiple application of a two-point method markedly prolonging breath cycle time, or with the “super syringe” method, which uses an unphysiologic “giant” breath.

Computer-based signal processing now available at the bedside can evaluate all measured data points and are therefore referred to as multipoint methods. In a previous publication, we presented a multipoint method for determining an average for respiratory system compliance and resistance over the whole breath by application of the resistance-compliance model (eq [1]) onto all sample points of the loop of pressure, volume, and flow.

\[
\text{Paw}(t) = V(t)/\text{Ctrs} + \dot{V}(t)\cdot\text{Rtrs} + K \tag{1}
\]

Airway pressure Paw(t) is the sum of the elastic pressure component (V(t)/Ctrs), the resistive pressure component (\(\dot{V}(t)\cdot\text{Rtrs}\)), and a pressure component K, which reflects airway pressure if both elastic and resistive pressure components equal zero. Compliance (Ctrs), resistance (Rtrs), and K are calculated by means

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of the least-squares fit procedure using all measured values for airway pressure Paw(t), volume V(t), and flow V(t) of one breath.\textsuperscript{13,14}

To test the quality of the results we recalculate airway pressure point by point according to equation 1, using the previously calculated values for Ctrs, Rtrs, and K and the measured values for volume and flow. This gives the recalculated P/V loop of the RC model. We then superimpose the measured and the recalculated P/V loops and obtain the difference in pressure as a quantitative measure of the accuracy of the calculated Ctrs, Rtrs, and K. The lower the difference, the better the correspondence of the two P/V loops and the higher the quality of the results.

Using our original method in daily routine, we saw an excellent correspondence in patients after open heart surgery,\textsuperscript{12} but poor in patients with severe ARDS.\textsuperscript{15} Especially late in inspiration and early in expiration we observed a lack of correspondence in ARDS patients. We therefore hypothesized that the nonlinearity of compliance—predominantly attributed to the respiratory system—and resistance—predominantly attributed to the endotracheal tube—could be the explanation. It is the purpose of this study to investigate whether the quality of Ctrs and Rtrs in ARDS patients can be improved by excluding those data sequences that are predominantly influenced by nonlinear properties of the respiratory system and the endotracheal tube.

**METHODS**

**Patients**

We investigated 17 mechanically ventilated patients, five patients without pulmonary disease after open-heart surgery (HEART group), and 12 patients with severe ARDS after polytrauma and/or sepsis (ARDS group, definition according to Ralph et al\textsuperscript{4}). Clinical data of the ARDS patients are listed in Table 1. A description of the respiratory situation of the patients is given in Table 2. Patients were ventilated with constant inspiratory flow using one ventilator (M-250, Monaghan, Denver) in the HEART group and a different ventilator (EV-A, Dräger, Lübeck, Germany) in the ARDS group. All measurements were taken with the patients paralyzed (pancuronium bromide) in a supine position, and under steady-state conditions. The study was approved by the Hospital Ethics Committees.

Flow and airway pressure were measured at the proximal endotracheal tube. Gas flow was measured with a heated pneumotachograph (Fleisch No. 2, Metabo, Epalinges, Switzerland) connected to a differential pressure transducer (FC940, Furness Controls, Bexhill, UK), airway pressure with a pressure transducer.

<table>
<thead>
<tr>
<th>Patient/Sex/Age, yr</th>
<th>Clinical Course</th>
<th>APV, rel*</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/M/70</td>
<td>Laparotomy for bleeding ventricular ulcer, bronchopneumonia, septicemia, MOF,\textsuperscript{†} ARDS</td>
<td>92</td>
<td>Died</td>
</tr>
<tr>
<td>2/M/60</td>
<td>Multiple trauma with brain damage, laparotomy and trepanation, hemorrhagic shock, acute respiratory failure, ARDS</td>
<td>59</td>
<td>Discharged from hospital</td>
</tr>
<tr>
<td>3/M/75</td>
<td>Abdominoperitoneal resection of the rectum for rectum carcinoma, relaparotomy for volvulus, aspiration, ARDS</td>
<td>65</td>
<td>Died</td>
</tr>
<tr>
<td>4/F/56</td>
<td>Laparotomy for bleeding ulcer, bronchopneumonia, septicemia, ARDS</td>
<td>62</td>
<td>Discharged from hospital</td>
</tr>
<tr>
<td>5/M/50</td>
<td>Decortication for pleural empyema following chronic osteitis, septicemia, ARDS</td>
<td>68</td>
<td>Discharged from hospital</td>
</tr>
<tr>
<td>6/M/73</td>
<td>Coronary artery bypass graft, aortic balloon pumping, cholecystectomy for acute cholecystitis, bronchopneumonia, MOF, ARDS</td>
<td>38</td>
<td>Died</td>
</tr>
<tr>
<td>7/M/64</td>
<td>Chest wall resection for chondrosarcoma, bronchopneumonia, septicemia, ARDS</td>
<td>58</td>
<td>Died</td>
</tr>
<tr>
<td>8/M/79</td>
<td>Hemicolectomy for colon carcinoma, relaparotomy for peritonitis, bronchopneumonia, septicemia, MOF, ARDS</td>
<td>51</td>
<td>Died</td>
</tr>
<tr>
<td>9/F/65</td>
<td>Cholecystectomy for gallbladder perforation, peritonitis, bronchopneumonia, ARDS</td>
<td>31</td>
<td>Discharged from hospital</td>
</tr>
<tr>
<td>10/M/47</td>
<td>Multiple trauma, fracture of vertebral column, bowel resection, septicemia, ARDS</td>
<td>38</td>
<td>Discharged from hospital</td>
</tr>
<tr>
<td>11/M/33</td>
<td>Multiple trauma, hemorrhagic shock, acute respiratory failure, ARDS</td>
<td>34</td>
<td>Died</td>
</tr>
<tr>
<td>12/M/59</td>
<td>3 laparotomies for recurrent bleeding ventricular ulcer, hemorrhagic shock, bronchopneumonia, septicemia, MOF, ARDS</td>
<td>57</td>
<td>Died</td>
</tr>
</tbody>
</table>

*APV = accessible pulmonary volume in percent of expected FRC\textsuperscript{10} (sitting posture), determined by nitrogen washout.
†MOF = multiple organ failure.

Table 1 — Clinical Course of ARDS Patients Preceding the Investigation

<table>
<thead>
<tr>
<th>Patient/Setting</th>
<th>HEART Group (Mean/SD)</th>
<th>ARDS Group (Mean/SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=5</td>
<td>n=12</td>
<td></td>
</tr>
<tr>
<td>RR, min\textsuperscript{-1}</td>
<td>6.2 ± 0.5</td>
<td>13.9 ± 1.5</td>
</tr>
<tr>
<td>Vr, ml-BTPS</td>
<td>1,139 ± 164</td>
<td>977 ± 105</td>
</tr>
<tr>
<td>Vlm, ml-BTPS/s</td>
<td>690 ± 216</td>
<td>524 ± 66</td>
</tr>
<tr>
<td>EIP, ms</td>
<td>1,131 ± 536</td>
<td>990 ± 91</td>
</tr>
<tr>
<td>PEEP, mbar</td>
<td>1.2 ± 0.3</td>
<td>12.5 ± 3</td>
</tr>
<tr>
<td>FIO\textsubscript{2}</td>
<td>0.4 ± 0</td>
<td>0.6 ± 0</td>
</tr>
<tr>
<td>Pulmonary gas volume, ml</td>
<td>1,605 ± 407</td>
<td>2,249 ± 829</td>
</tr>
<tr>
<td>PaO\textsubscript{2}, mm Hg</td>
<td>138 ± 33</td>
<td>135 ± 53</td>
</tr>
<tr>
<td>PaCO\textsubscript{2}, mm Hg</td>
<td>36 ± 3</td>
<td>38 ± 6</td>
</tr>
<tr>
<td>Q'S/Q'T, %</td>
<td>7 ± 5</td>
<td>19 ± 9</td>
</tr>
<tr>
<td>Cl, L/min/m\textsuperscript{2}</td>
<td>1.7 ± 0.8</td>
<td>2.5 ± 0.9</td>
</tr>
<tr>
<td>Paw, mbar</td>
<td>20 ± 5</td>
<td>40 ± 8</td>
</tr>
<tr>
<td>Paw,m, mbar</td>
<td>6 ± 1</td>
<td>29 ± 6</td>
</tr>
<tr>
<td>IPEEP, mbar</td>
<td>0 ± 0</td>
<td>16 ± 3</td>
</tr>
<tr>
<td>Vte, ml/s</td>
<td>3 ± 3</td>
<td>320 ± 144</td>
</tr>
</tbody>
</table>

*See text for expansion of abbreviations.
†Determined by N, washout.
Two-Point Calibration

Two-Point data were obtained from one ARDS patient. Data discarded from evaluation with the LOOP method are marked by rectangles: 1, inspiratory flow ramp (0 to 20 percent of the time of the inspiratory flow phase); 2, end-inspiratory flow ramp (80 to 100 percent of the time of the inspiratory flow phase), end-inspiratory pause (EIP), expiratory flow up to the inflection point (IP: maximum slope); 3, end-expiratory samples with flow values less than 20 ml/s or at least the last four end-expiratory samples.

(SZ75120, Sensym, UK). The sensors were fitted to the measuring site through three silicone hoses (180 cm long, 4 mm internal diameter [ID]). To correct the flow for changes in gas viscosity, dry gas fractions were measured using a quadrupole mass spectrometer (MGA-200, Centronic, Croydon, UK), connected by a 3.5-m-long, 0.38-mm-ID PP20 polyethylene capillary (Portex, Hythe Kent, UK). The preprocessed analog flow, pressure, and gas concentration signals were sampled and digitized at a rate of 60 Hz and stored digitally for the offline analysis. To determine lung volume, we modified the M-250 ventilator for nitrogen washout; the EVA ventilator was modified by the manufacturer. The details of our nitrogen washout technique, including synchronization of the flow and concentration signals, are described elsewhere.

In each patient, three breathing patterns were investigated consecutively: (1) the reference pattern without EIP; (2) the same pattern with EIP; and (3) the reference pattern again. The IPEEP was determined by means of an end-expiratory occlusion maneuver. For each pattern, analog data were digitized (60 Hz) and raw data were stored on disk. A series of 15 consecutive breaths with identical and undisturbed flow pattern was analyzed breath by breath. The results presented herein are the mean values of these 15 consecutive breaths.

### Table 3—Compliance Corrected for IPEEP and Resistance Determined with the Two-Point Methods and with the Multipoint Method LOOP*

<table>
<thead>
<tr>
<th>Multipoint Method Loop</th>
<th>Two-Point Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ctrs, ml/bar</td>
</tr>
<tr>
<td>HEART n = 5</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>73</td>
</tr>
<tr>
<td>SD-inter</td>
<td>9</td>
</tr>
<tr>
<td>SD-intra</td>
<td>0.4</td>
</tr>
<tr>
<td>ARDS n = 12</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>46</td>
</tr>
<tr>
<td>SD-inter</td>
<td>11</td>
</tr>
<tr>
<td>SD-intra</td>
<td>1</td>
</tr>
</tbody>
</table>

*SD-inter = interindividual standard deviation; SD-intra = intraindividual standard deviation (15 analyzed breaths per patient); CsST = semistatic compliance (HEART patients); CsST,IP = semistatic compliance corrected for intrinsic PEEP (ARDS patients); RsST = semistatic resistance; K = airway pressure if V(t) = 0 and V(t) = 0 (equation 1). See text for expansion of other abbreviations.

### Figure 1: Flow vs time diagram of a mechanical breath obtained from one ARDS patient. Data discarded from evaluation with the LOOP method are marked by rectangles: 1, inspiratory flow ramp (0 to 20 percent of the time of the inspiratory flow phase); 2, end-inspiratory flow ramp (80 to 100 percent of the time of the inspiratory flow phase), end-inspiratory pause (EIP), expiratory flow up to the inflection point (IP: maximum slope); 3, end-expiratory samples with flow values less than 20 ml/s or at least the last four end-expiratory samples.

### Figure 2: Top: Airway pressure vs time of two consecutive breathing cycles. The first cycle includes an end-inspiratory pause (EIP) shortening the expiratory time. The inspiration of the second cycle is replaced by an occlusion maneuver to get IPEEP. Bottom: Airway pressure vs time curve magnified at the EIP. The curve is averaged from 15 consecutive breaths without IPEEP maneuver. The pressure P1 immediately following occlusion (marked by a cross) is determined as the mean value of the first minimum (min) and the first maximum (max) of the low frequency pressure oscillation.

#### Multipoint Method

Simultaneously measured values for airway pressure (Paw), flow (V), and volume (V), make a Paw-V-V-triple. With a respiratory rate

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of 10/min and an A/D rate of 60 Hz, this yields 360 Paw-V-V-triples per breath that all must comply with equation 1. Thus, the coefficients Ctrs, Rtrs, and K of equation 1 can be determined by means of the least-squares fit algorithm. In the multipoint method to be presented (LOOP), the samples to be excluded from further evaluation are defined as follows (Fig 1): (1) Inspiratory flow ramp (from 0 to 20 percent of the time of the inspiratory flow phase). (2) End-inspiratory flow ramp (from 80 to 100 percent of the time of the inspiratory flow phase), end-inspiratory pause (EIP), and expiratory flow up to the inflection point (IP). The IP, which is defined as the point of maximum slope of the expiratory flow curve following the expiratory peak flow, is determined by means of a moving window algorithm, including four consecutive flow samples; breath-by-breath reproducibility was ± two samples or ±33 ms, respectively. (3) End-expiratory samples less than 20 ml/s or at least the last four end-expiratory samples.

Two-Point Methods

As reference methods, we used two-point methods. A breathing pattern, including an EIP was therefore applied. In the HEART patients, the end-expiratory flow was zero (mean: 3 ml/s), so we could assume no intrinsic PEEP. In the ARDS group, IPEEP was assessed with an occlusion maneuver, and semistatic compliance was corrected for intrinsic PEEP according to Rossi et al: CsST,IP = Vr/(Pawl-IPEEP) (Fig 2). Semistatic resistance (RsST) was determined according to Milic-Emili and to Rossi et al. During the EIP, RsST equals the pressure drop following occlusion divided by the flow immediately before occlusion. The pressure drop across the resistive airways is calculated as inspiratory peak pressure (Paw,max) minus the pressure immediately after occlusion, which is called Pp: RsST = (Paw,max-Pp)/V. To avoid disturbances by noise, the resistive pressure drop was determined from a pressure curve averaged point by point out of 15 breaths (Fig 2).

The accuracy of the compliance values obtained with the LOOP method was tested by comparison with the reference values CsST,IP. There is no adequate reference method for the resistance. Never-

![Diagram](image_url)

**Figure 3.** Relationship between the compliance of the total respiratory system calculated using LOOP (Ctrs) and the semistatic compliance corrected for intrinsic PEEP (CsST,IP). Filled triangles are values of 12 ARDS patients and open triangles are values of five HEART patients. The solid line is the line of identity.

![Diagram](image_url)

**Figure 4.** Relationship between the resistance of the total respiratory system calculated using LOOP (Rtrs) and the semistatic resistance (RsST). Filled triangles are values of 12 ARDS patients and open triangles are values of five HEART patients. The solid line is the line of identity.

The HEART patients displayed "nearly normal" respiratory data, whereas the ARDS patients, who were ventilated with a high respiratory rate and PEEP, were characterized by high maximum airway pressure, end-expiratory flow, and by a sizable intrinsic PEEP (Table 2). The compliance of the ARDS patients was 40 percent reduced compared with the HEART patients (Table 3).

In both patient groups, the LOOP method yielded compliance values practically identical (no significant difference) to the reference value CsST,IP (Table 3). The differences between the individual Ctrs and CsST,IP values were minimal (Fig 3). In the HEART patients, the LOOP method yielded a resistance value that corresponds well with the reference value RsST (no significant differences). In the ARDS patients, the reference value was 20 percent lower than the resistance value from LOOP (p<0.05). The relationship between the Rtrs and the RsST value is summarized in Figure 4. In the ARDS patients, the IPEEP determined with the end-expiratory occlusion tech-

Compliance and Resistance in Ventilated ARDS Patients (Guttmann et al)

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FIGURE 5. Relationship between the pressure K calculated using LOOP and the intrinsic PEEP measured with the end-expiratory occlusion maneuver. Filled triangles are values of 12 ARDS patients. The solid line is the line of identity.

The small root-mean-square error of fitting (rms) indicates that the application of the LOOP method improves the correspondence between measured airway pressure and calculated airway pressure (Fig 6 and 7). In the HEART patients, rms is 0.35 mbar (original multipoint method, 0.45 mbar). In the ARDS patients, the mean rms is 1.0 mbar (original multipoint method, 1.9 mbar; significant reduction: 95 percent confidence interval for mean rms difference, 0.6 to 1.0 mbar).

The multipoint method LOOP gives lower values for the intranindividual standard deviations than the two-point methods (Table 3) indicating its better reproducibility. In about 500 analyses performed to date, the LOOP algorithm has manifested its excellent reliability. No failure has been observed.

DISCUSSION

We propose a computer-assisted method for online breath-by-breath determination of compliance and resistance at the bedside. The method deals with the linear parts of the whole pressure-volume-flow loop. It is therefore a multipoint method that we call LOOP. The modification in respect to the original method is the exclusion of nonlinear portions of the P/V loop.

Our study shows that the proposed modified multipoint method LOOP reliably estimates Ctrs not only in "nearly normal" lungs (HEART group), but also in severely diseased lungs such as ARDS (ARDS group) as compared with the standard two-point method. The main advantage of the method is sufficiently confirmed: there is no need to alter the ventilatory pattern and no special maneuvers are required to make the measurements. Finally, ltrls can be determined routinely.

Our hypothesis was that nonlinearity of compliance

FIGURE 6. P/V loop from one breath of one ARDS patient. The measured data are represented as single points; the resynthesized loop on the basis of C and R estimated with the original multipoint method is superimposed (solid line). The correspondence between the measured and the model curve is directly visible as pressure difference ΔPaw(t).

FIGURE 7. PV loop analogous to Figure 6 (same data). The selected sample range for LOOP is marked by short horizontal bars. The calculated model curve (solid line) is drawn within the selected sample range. Note the improved correspondence between the measured and the calculated loop.
and resistance is the cause of the lack of correspondence between the Paw predicted by the RC model and the measured data, and therefore that exclusion of data influenced by nonlinear effects should improve the results. To test our hypothesis, we simulated a volume-controlled breath with the computer (see appendix). We simulated volume, flow, and pressure curves with and without nonlinear resistance and compliance. Nonlinear resistance was simulated including the nonlinear resistance (Rohrer) coefficient of an endotracheal tube (Nt 7.5). For the nonlinear compliance, we assumed a steady reduction from 100 percent down to 75 percent when inflated volume rises from 60 percent to 100 percent. The simulation was based on the ventilatory data of one of our ARDS patients. The simulated data set was analyzed with LOOP and with the original multipoint method. The results are shown in Figure 8. When resistance and compliance are linear, the P/V loops of the RC model and the simulated patient are congruent (Fig 8a and 8b). In the presence of nonlinear resistance and compliance, however, the two loops diverge, delineating the difference at the end of inspiration with its maximum at the beginning of expiration (Fig 8c and 8d). This is analogous with the situation we found in our ARDS patients. The results of this simulation indicate that LOOP mainly eliminates the influences of nonlinear tube resistance and of nonlinear compliance.

In our ARDS patients, the data sequences eliminated by LOOP are characterized by large flow and volume values. The expiratory peak flow was 1,600 ml/s (mean value). Due to this high flow, turbulent effects are dominant. Turbulent flow occurs whenever the inertial forces dominate the viscous forces. The Reynolds number (Re) indicates the relative effects of inertial and viscous forces within the gas. The expiratory peak gas flow of our ARDS patients within an endotracheal tube of 7.5 mm ID is characterized by a Reynolds number of Re = 18,300, indicating turbulent
flow (a Reynolds number exceeding 2,300 indicates turbulence). Consequently, the flow resistance and pressure drop across the endotracheal tube must show a nonlinear flow-dependent increase. Given that the endotracheal tube is the predominant nonlinear resistive element within the total respiratory system, the LOOP method reduces the effects of its nonlinearity.

In the ARDS patients, the nonlinearity of compliance causes airway pressure to increase even more toward the end of inspiration. Since LOOP eliminates sequences with large lung volume from the analysis, the effects of compliance nonlinearity are markedly reduced.

The pressure $K$ (equation 1) is the remaining alveolar pressure at end-expiration where both $V(t)$ and $\dot{V}(t)$ equal zero and therefore represents dynamic intrinsic PEEP. Thus, LOOP includes a reliable determination of IPEEP by means of the predominantly linear part of the alveolar pressure curve. This is the predominant reason for the nearly perfect correspondence of its compliance results with those of the semistatic methods explicitly corrected for intrinsic PEEP assessed by the occlusion maneuver. In the last few years, it has been shown that intrinsic PEEP is a common phenomenon in ARDS patients. Any method for determining compliance should therefore cope with intrinsic PEEP. Our LOOP method fulfills this requirement and there is no need for either an additional maneuver to measure intrinsic PEEP or for a breathing pattern with an EIP.

However semistatic resistance was 20 percent lower than the resistance obtained with LOOP. The resistance determined with a multipoint method is a mean value over the whole breath taking into consideration both inspiratory and expiratory resistive components. Therefore, there are still parts with relatively high flow that the LOOP method is dealing with leading to accordingly higher values for resistance. In contrast, the two-point method zooms at one point at the end of inspiration with low inspiratory flow and cannot yield an $R$ value representative of the whole breath cycle. In the presence of flow-dependent resistive components, the resistance calculated with any multipoint method systematically exceeds $R_{st}$ determined with an EIP.

In summary, we present a modified multipoint method LOOP for determination of compliance and resistance as well as dynamic intrinsic PEEP if present. The method uses selected data of the pressure-volume-flow loop. To exclude the typical nonlinearities of compliance and resistance, the data set to be analyzed is restricted to the constant inspiratory flow section and to the steadily decreasing expiratory flow section after IP. Without the need for any special breathing pattern or any special maneuver, Ctrs, Rtrs, and IPEEP can be determined instantaneously and reliably, on a breath-by-breath basis, at the bedside.

**APPENDIX**

The simulation of a volume-controlled breath is based on constant inspiratory flow ($\dot{V}(t)$) and steady-state conditions for a specific respiratory rate, i.e., each breath starts with a tidal volume that equals the end-expiratory volume of the preceding breath; the measuring site for flow and airway pressure is between the Y-piece and the endotracheal tube. The time step between the simulated data points equals 16 ms.

The components of the simulation are as follows: respiratory rate (RR); constant resistance ($R$); constant resistance of the tubing ($R_{ex}$); endotracheal tube with coefficients of linear resistance ($K_1$) and of nonlinear resistance ($K_2$, according to Rohrer); end-expiratory alveolar pressure $P_{alvee}$; and nonlinear compliance ($C = f(V)$). Compliance is assumed to be constant up to $V = 0.6 V_T$ and to decrease with a constant slope up to 75 percent of its initial value at $V = 1.0 V_T$.

The volume, flow, and pressure data points are calculated separately for inspiration (i, number of inspiratory samples) and for expiration (e, number of expiratory samples).

**Inspiration:**

$$V(i=0) = V(TE)$$

$$V(i) = \sum \dot{V} t \cdot 16 \text{ ms} + V(i=0)$$

$$\dot{V}(i) = \dot{V} I$$

$$P_{aw}(i) = V(i)/C(V(i)) + \dot{V}(i)/(K_1 + R) + \dot{V}(i)^2 + \dot{V}(i)/K_2 + P_{alvee}$$

**Expiration:**

$$V(e=0) = V(TE)$$

$$V(e) = V(e-1) - V(e-1) \cdot 16 \text{ ms}$$

$$\dot{V}(e) = - \frac{R + R_{ex} + K_1}{2 K_2}$$

$$+ \left( \frac{R + R_{ex} + K_1}{2 K_2} \right)^2 + \frac{V(e)}{C \cdot K_2}$$

$$P_{aw}(e) = V(e)/C(V(e)) - \dot{V}(e)/(R + K_1) + \dot{V}(e)^2 + \dot{V}(e)/K_2 + P_{alvee}$$

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