Effects of Thoracotomy on Respiratory System, Lung, and Chest Wall Mechanics*

Ana Claudia M. Rodrigues; Lucio F. Pacheco Moreira; Cláudia L. de Souza, M.D.; Paola Capparelli D. Pettersen; Paulo Hilário N. Saldiva, M.D., F.C.C.P., Ph.D.; and Walter A. Zin, M.D., Ph.D.

Nineteen rats were sedated, anesthetized, paralyzed, and mechanically ventilated. The respiratory, lung, and chest wall elastances (Estd, Est-L, Est-w); respiratory system, pulmonary, and chest wall total resistances (Rtot-rs, Rtot-L, Rtot-w); respiratory system, pulmonary, and chest wall initial resistances (Rinit-rs, Rinit-L, Rinit-w); and respiratory system, pulmonary, and chest wall difference resistances (Rdiff-rs, Rdiff-L, Rdiff-w) were determined before and after thoracotomy using the end-inflation occlusion method. Rinit reflects the Newtonian resistances and Rdiff represents the viscoelastic/inhomogeneous pressure dissipations in the system. Rtot = Rinit + Rdiff, ie, total resistance. The animals were submitted to either anterolateral thoracotomy (group A, n = 7), median sternotomy (group B, n = 6), or median sternotomy under PEEP while the lungs were exposed (group C, n = 6). In groups A and B, statistically significant increases in Rdiff-rs significantly augmented Rtot-rs. The former results were entirely secondary to significant increases in Rdiff-L, which naturally raised Rtot. Resistance was not altered in group C rats. Thus, anterolateral thoracotomy and median sternotomy increases Rtot-rs as a consequence of augmented Rdiff-L, but this finding could be prevented by the use of PEEP. Est-rs and Est-L increased in the three groups after surgery. Groups D and E were comprised of four animals each. Both underwent median sternotomy and in group E, PEEP was applied. Histopathologic examination of the lungs demonstrated a higher degree of lung collapse in group D.

**Chest 1993; 104:1882-96**

Thoracotomy frequently leads to respiratory impairment. Although a few studies on respiratory mechanics related to thoracotomy have been reported, there are some important aspects still unexplored. Most of the previous works assessed total respiratory system mechanics or spirometric parameters and reported conflicting results attributable to the diversity of methods used. Pulmonary elastance was found to increase after thoracotomy. Recently, respiratory system mechanics have been partitioned into lung and chest wall components in patients undergoing open-chest cardiac surgery. However, no data have been hitherto reported concerning respiratory system, lung, and chest wall mechanics before and after thoracotomy performed under circumstances of no underlying pathologic condition.

**From the Instituto de Biofísica Carlos Chagas Filho, Universidade Federal do Rio de Janeiro, Ilha do Fundão, Rio de Janeiro, and Laboratório de Poluição Atmosférica Experimental, and Instituto de Coração, Faculdade de Medicina da Universidade de São Paulo, São Paulo, Brazil. Supported by the Brazilian Council for Scientific and Technical Development (CNPq), Financing for Studies and Projects (FINEP), Rio de Janeiro State Research Support Foundation (FAPERJ), São Paulo State Research Support Foundation (FAPESP), Laboratories of Medical Investigation (LIM-FMUSP), and Graduate Teaching and Research Council of the Federal University of Rio de Janeiro (CEPG-UFRJ).**

*Reprint requests: Dr. Rodrigues, Universidade Federal do Rio de Janeiro, Instituto de Biofísica Carlos Chagas, Centro de Ciencias de Saúde, G. Ilha do Fundão, 21949-900 Rio de Janeiro, RJ, Brazil*
mechanical parameters.

Therefore, in the present study, respiratory mechanics were evaluated by means of sudden airway occlusions at end-inspiration under constant flow inflation of the lungs. Although this method has been used for a long time, the significance of the measured variables has only recently been clarified. 14,16,21-23 Hence, the interrupter method provides a means of obtaining Rinit, that selectively reflects the combination of airways and chest wall Newtonian resistances. 14,22,24 It also provides another quantity, Rdiff, with the units of resistance, that reflects stress relaxation or stress recovery properties of the lung and chest wall tissues, together with a tiny contribution of pendelluft in normal situations. 15,15,25,26 Finally, total resistance (Rtot) is equal to the sum of Rinit and Rdiff.

MATERIALS AND METHODS

Three sets of experiments were performed. In the first, group A, 7 male Long-Evans rats (217 ± 3 [SD] g, range 213 to 220 g) were studied. In the second, 12 male Long-Evans rats randomly divided into two groups (group B: 215 ± 15 [SD] g, range 200 to 240 g, n = 6; and group C: 302 ± 14 [SD] g, range 290 to 330 g, n = 6) were analyzed. In the third, 8 male Long-Evans rats randomly divided into two groups (group D: 272 ± 32 [SD] g, range 240 to 300 g, n = 4; and group E: 304 ± 48 [SD] g, range 240 to 355 g, n = 4) were used. The animals were initially sedated with diazepam (5 mg intraperitoneally) and anesthetized with pentobarbital sodium (20 mg/kg intraperitoneally), and a snugly fitting cannula (1.5 mm ID) was introduced into the trachea under direct vision aided by a small laryngoscope. The animals were then placed in the supine position on a heated surgical table, paralyzed with succinylcholine chloride (5 mg/kg intraperitoneally), and mechanically ventilated with a constant-flow ventilator. When desired, an end-inspiratory pause could be generated by adjusting the ventilator settings.

Group A animals underwent left anterolateral thoracotomy at the level of the fifth intercostal space, and rats belonging to groups B, C, D, and E were submitted to median sternotomy. Positive end-expiratory pressure was applied to the airways of open-chest rats belonging to groups C and E. The PEEP level was determined as follows: before the pleural space was opened, the ventilator was disconnected at end expiration and the airways were occluded. After pleural incision, there was an increase in tracheal pressure (Ptr) that corresponded to the elastic recoil pressure of the lung at relaxation volume (Vr) in the anesthetized rat. Thereafter, the same pressure was applied to the lung as a PEEP Respiratory mechanics were studied before surgery and right after chest wall closure in animals of groups A, B, and C. The chest wall remained open for 20 ± 4 (SD) min. Morphologic examination was performed on lungs belonging to rats of groups D and E.

An adequate pneumotachograph, as described by Mortola and Noworaj,25 was connected to the tracheal cannula for the measurement of airflow, and by electronic integration, changes in lung volume. The flow resistance of the equipment (tracheal cannula included) was constant up to flow rates of 26 ml/s and amounted to 0.03 cm H2O·ml−1·s−1. The flow resistance of the equipment was subtracted when appropriate, so that the results reported in this study represent the intrinsic resistance values of the rats. Because abrupt changes in diameter were not present in our circuit, errors of measurement of flow resistance were probably avoided. Equipment dead space was 0.4 ml. Tracheal pressure was measured with a Hewlett-Packard 270 differential pressure transducer (Waltham, Mass). Changes in esophageal pressure (Pes) were measured with a 30-cm-long water-filled catheter (PE-240) with side holes at the tip connected to a F823-2D-300 Statham differential pressure transducer (Hato Rey, Puerto Rico). The catheter was placed into the stomach and then slowly returned to the esophagus; its proper positioning was assessed using the “occlusion test.”26 This consisted of comparing ΔPes and ΔPtr during spontaneous inspiratory efforts subsequent to airway occlusion at end expiration. In all instances ΔPes was close to ΔPtr, the difference not exceeding 3 percent. Then, to the other part of the transducer, the Ptr signal was connected so that changes in transpulmonary pressure (Pl = Ptr – Pes) were thereafter registered. The frequency responses of the pressure measurement systems (Ptr and Pl) were flat up to 20 Hz, without appreciable phase shift between the signals. All the signals were conditioned and amplified in a Beckman type R Dynograph (Schiller Park, Ill) and recorded on paper at speeds of 25 and 50 mm/s.

For the determination of respiratory mechanics, flow (V), Ptr, and Pl signals were also low-pass filtered (100 Hz), sampled at 200 Hz with a 12-bit analog-to-digital converter (DT2801A, Data Translation, Marlboro, Mass), and stored on a computer (PC-AT, IBM, Armonk, NY). The analysis was performed off-line from rapid end-inspiratory airway occlusions during constant-flow inflations, as previously described.25 After end-inspiratory occlusion, there is a fast initial drop in Ptr (ΔPinit-rs) from the preocclusion value up to an inflection point followed by a slower pressure drop (ΔPdiff-rs) to a plateau. This plateau corresponds to the elastic recoil pressure of the respiratory system. ΔPinit-rs and ΔPdiff-rs divided by the flow immediately preceding the occlusion provide Rinit-rs and Rdiff-rs, respectively. ΔPinit-rs + ΔPdiff-rs divided by flow gives the total respiratory system resistance (Rtot-rs). The same procedures apply to Pl, yielding the values of Rtot-L, Rinit-L, and Rdiff-L. The Rtot-w, Rinit-w, and Rdiff-w were calculated by subtracting the pulmonary from the corresponding respiratory system values. Respiratory system and lung elastances (Est-rs and Est-L, respectively) were calculated by dividing the corresponding elastic recoil pressures (Pel-rs and Pel-L, respectively) by tidal volume (Vt). Chest wall elastance (Est-w) was calculated by subtracting Est-L from Est-rs. Five to 10 determinations were performed in each animal before and after surgery. Prior to each data collection period, the airway contents were aspirated to remove possible mucus collection, and the respiratory system was inflated to total lung capacity (Pl = 30 cm H2O). The maneuver was repeated three times. Because a mechanical occlusion valve always takes a finite time to close, V never drops immediately to zero upon interruption. The V passing through the valve as it shuts increases the pressures, and thus, may lead to an overestimation of Rtot and Rinit.27,28 The closing time of the valve used in the ventilator within the experimental range of inspiratory flows was 10 ms. The delay was allowed for by backextrapolation of the pressure records to the actual time of occlusion, and the corrections in resistance, although very minute, were performed as previously described.25

Morphologic analysis was performed in excised lungs at Vr. After the end of surgery, the animals belonging to groups D and E were killed by sectioning the abdominal aorta. The trachea was exposed at the neck level and securely tied. The thorax was reopened and the lungs removed, frozen in liquid nitrogen, fixed in Carnoy’s solution, embedded and stained with hematoxylin-eosin. Lung tissue was sampled by sagittal section of the left lung at the level of the axial bronchus. In each rat, the analysis was performed in six random, noncoincident, ×100 microscopic fields, by counting the times that a 100-µm-long straight line intercepted alveoli.

In order to eliminate the pneumothorax in all instances, the last stitch was made while the lungs were inflated up to total lung capacity. Right after chest wall closure, the lungs underwent radioscopic examination in an attempt to identify the presence of pneumothorax or any other undesirable alteration.

All animals received humane care in compliance with the “Principles of Laboratory Animal Care” formulated by the National Society for Medical Research and the “Guide for the Care and Use
Table 1 — Mean Values Before and After Thoracotomy

<table>
<thead>
<tr>
<th></th>
<th>Anterolateral Thoracotomy</th>
<th>Median Sternotomy</th>
<th>Median Sternotomy + PEEP</th>
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<tbody>
<tr>
<td></td>
<td>Control</td>
<td>After ALT</td>
<td>Control</td>
</tr>
<tr>
<td>Flow, ml/s</td>
<td>6.66 ± 0.43</td>
<td>6.56 ± 0.41</td>
<td>7.23 ± 0.62</td>
</tr>
<tr>
<td>Tidal volume, ml</td>
<td>1.00 ± 0.09</td>
<td>0.99 ± 0.07</td>
<td>1.27 ± 0.05</td>
</tr>
<tr>
<td>Rtot-rs, cm H₂O ml⁻¹s</td>
<td>0.170 ± 0.044</td>
<td>0.227 ± 0.068†</td>
<td>0.178 ± 0.024</td>
</tr>
<tr>
<td>Rinit-rs, cm H₂O ml⁻¹s</td>
<td>0.078 ± 0.039</td>
<td>0.098 ± 0.068</td>
<td>0.065 ± 0.017</td>
</tr>
<tr>
<td>Rdiff-rs, cm H₂O ml⁻¹s</td>
<td>0.063 ± 0.016</td>
<td>0.130 ± 0.021†</td>
<td>0.124 ± 0.009</td>
</tr>
<tr>
<td>Rtot-L, cm H₂O ml⁻¹s</td>
<td>0.094 ± 0.055</td>
<td>0.171 ± 0.083†</td>
<td>0.090 ± 0.026</td>
</tr>
<tr>
<td>Rinit-L, cm H₂O ml⁻¹s</td>
<td>0.096 ± 0.037</td>
<td>0.079 ± 0.074</td>
<td>0.028 ± 0.015</td>
</tr>
<tr>
<td>Rdiff-L, cm H₂O ml⁻¹s</td>
<td>0.056 ± 0.026</td>
<td>0.062 ± 0.019†</td>
<td>0.062 ± 0.016</td>
</tr>
<tr>
<td>Rtot-w, cm H₂O ml⁻¹s</td>
<td>0.076 ± 0.032</td>
<td>0.057 ± 0.037</td>
<td>0.090 ± 0.024</td>
</tr>
<tr>
<td>Rinit-w, cm H₂O ml⁻¹s</td>
<td>0.040 ± 0.035</td>
<td>0.019 ± 0.018</td>
<td>0.028 ± 0.017</td>
</tr>
<tr>
<td>Rdiff-w, cm H₂O ml⁻¹s</td>
<td>0.036 ± 0.020</td>
<td>0.038 ± 0.021</td>
<td>0.062 ± 0.015</td>
</tr>
<tr>
<td>Est-rs, cm H₂O ml⁻¹s</td>
<td>5.120 ± 0.866</td>
<td>5.745 ± 0.703†</td>
<td>3.783 ± 0.548</td>
</tr>
<tr>
<td>Rdiff-L, cm H₂O ml⁻¹s</td>
<td>3.961 ± 0.903</td>
<td>4.574 ± 0.600†</td>
<td>2.984 ± 0.536</td>
</tr>
<tr>
<td>Est-L, cm H₂O ml⁻¹s</td>
<td>1.160 ± 0.323</td>
<td>1.171 ± 0.457</td>
<td>0.801 ± 0.271</td>
</tr>
</tbody>
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<sup>*ALT = anterolateral thoracotomy; MS = median sternotomy; MS + P = median sternotomy plus PEEP.</sup>

<sup>†p<0.05 compared to respective control value.</sup>

of Laboratory Animals" prepared by the National Academy of Sciences.

Statistical analysis was performed by means of the Student's paired and unpaired t tests, the significance level established at 5 percent. Values are means ± SD unless otherwise specified.

RESULTS

Table 1 shows the mean values of constant inspiratory flow, VT, and respiratory system, lung, and chest wall resistances and elastances both before and after thoracotomy in rats belonging to groups A to C. Surgery modified the respiratory mechanical profile. In rats submitted to anterolateral thoracotomy and median sternotomy without the use of PEEP, Rtot-rs was significantly increased because of a rise in Rdiff-rs. These were consequent to changes in pulmonary resistances only, since Rtot-L and Rdiff-L increased significantly. When PEEP was applied while the thorax was open, no changes in resistances could be detected. The overall resistance results are also depicted in Figure 1. Figure 2 shows that in all instances, surgery yielded a significant increase in Est-rs as a consequence of a higher Est-L.

Morphologic analysis demonstrated that in group D, 18.63 ± 3.20 (mean ± SD) alveoli were intercepted by a 100-µm-long straight line, whereas the corresponding values in group E were 10.75 ± 2.44. The means were significantly different.

Radiologic examination of the animals after chest wall closure did not display any abnormality.

DISCUSSION

Thoracotomy is frequently claimed to yield respiratory dysfunction. However, this conclusion was obtained from spirometric studies<sup>19</sup> and elastance determinations<sup>10-11</sup> performed days and weeks after operation. Recently, respiratory mechanical resistive and elastic profiles have been described in patients immediately after the end of thoracotomy with the patient still anesthetized and paralyzed.<sup>12,13</sup> Unfortunately, these studies were performed in patients with cardiac conditions submitted to extracorporeal cardiopulmonary bypass. Therefore, we decided to determine respiratory system, lung, and chest wall resistances and elastances in normal rats before and after thoracotomy. Two types of surgery were performed—anterolateral thoracotomy and median sternotomy. Furthermore, the effects of PEEP were also investigated. Morphometric analysis was also used to evaluate the pulmonary consequences of sternotomy with and without the use of PEEP.

It has been demonstrated in dogs<sup>14,30</sup> and rats<sup>31</sup> that Rinit-L essentially reflects airway resistance, ie, that the pulmonary tissues do not offer a Newtonian flow resistance. At least in cats<sup>24</sup> and dogs,<sup>16</sup> the chest wall contributes to Rinit-rs also. In humans, the contribution of Rinit-w to Rinit-rs was described,<sup>12</sup> but in another study, Rinit-w could not be identified.<sup>26</sup>

Rdiff can be closely related to stress relaxation or stress recovery properties of the lung and chest wall tissues (modeled by Kelvin bodies, each composed of an elastic element in parallel with a series elastance-resistance)<sup>25</sup>, together with a tiny contribution of pendelluft and asynchrony of movement within and between the chest wall components.<sup>14,25,31</sup> It is also possible that an increase in Rdiff comes from the obstruction of peripheral airways due to a decrease in lung volume and/or lung collapse after thoracotomy. In other words, Rdiff can reflect pressure losses due to viscoelastic properties and/or mechanical inhomogeneities of lung and chest wall. Since Rdiff is not a true Newtonian resistance, ΔPdiff could be used to describe the same phenomena but the conclusions would be similar.

Figure 1 shows that in groups A, B, and C, no

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changes in Rinit could be detected. On the other hand, in groups A and B, Rdif-L was significantly higher postoperatively (64.3 and 43.3 percent, respectively). Consequently, increases in Rtot-L (81.9 and 43.3 percent, respectively), Rdif-rs (39.8 and 24.2 percent, respectively), and Rtot-rs (33.5 and 29.8 percent, respectively) were also identified. Hence, airway and chest wall Newtonian resistances were not affected by surgery, but lung tissue resistance was increased postoperatively, independent of the incision used. There is only one report in which these resistances were also determined before and after thoracotomy. Their results differed from ours, but their patients presented either ischemic or valvular heart disease, ie, did not present normal lungs to start with. Thus, the direct comparison of their results to ours is not warranted.

In group C, a PEEP value high enough to keep Vr constant was maintained while the lungs were exposed. In this case, no significant changes in resistances could be evidenced, indicating that the use of PEEP under the present conditions is beneficial. Hitherto, this result has not been experimentally demonstrated in thoracotomy.

Thoracotomy increased Est-L in groups A, B, and C (15.5, 21.3, and 36.6 percent, respectively), notwithstanding the use of PEEP in the latter one. Est-rs was augmented accordingly (12.2, 19.7, and 31.8 percent, respectively). No alterations in Est-w were found. These results are in accordance with those previously reported in patients who underwent thoracotomy. Interestingly enough, in two of these studies, the postoperative measurements were performed some days after surgery, and in the other two, elastances were determined right after chest wall closure. Although in our experiments the respira-

**FIGURE 1.** Respiratory system (rs), pulmonary (L), and chest wall (w) resistances before (CTRL) and after surgery. Panels A, B, and C pertain, respectively, to anterolateral thoracotomy (ALT), median sternotomy (MS), and median sternotomy with the use of PEEP while the lungs were exposed (MS + P). Values are means (±SEM) of seven rats in ALT and six animals in MS and MS + P. Rs, Rtot, Rinit, and Rdif, total, initial, and difference resistances, respectively. Asterisk indicates statistically different from CTRL animals.

**FIGURE 2.** Respiratory system (rs), lung (L), and chest wall (w) static elastances (Est) before (CTRL) and after surgery. Panels A, B, and C pertain, respectively, to anterolateral thoracotomy (ALT), median sternotomy (MS), and median sternotomy with the use of positive end-expiratory pressure while the lungs were exposed (MS + P). Values are means (±SEM) of seven rats in ALT and six animals in MS and MS + P. Asterisk indicates statistically different from CTRL animals.
tory system had been inflated to total lung capacity before each measurement period, and also just prior to making the thoracic cavity airtight, the presence of microatelectasis could not be discarded by radiography.32

In order to demonstrate possible microscopic lung alterations, eight animals were studied. Rats in group D presented a significantly higher number of inter-cepted alveoli than those in group E. Hence, PEEP helped to decrease lung collapse while the chest remained open. This finding could explain the absence of significant changes in Rdiff-L in group C rats, but the increased Est-L found postoperatively in groups A, B, and C still requires clarification.

In conclusion, anterolateral thoracotomy and median sternotomy induced increases in pulmonary and respiratory system tissue resistances, which were prevented by using PEEP while the lungs remained exposed. Lung elastance was augmented in all instances. Histopathologic examination of the lungs demonstrated that those not submitted to PEEP presented a higher degree of lung collapse. Altogether, these data suggest that the peroperative use of PEEP could be beneficial during thoracotomy in humans, as previously suggested.33 Clearly, additional experiments are needed to clarify this point.

ACKNOWLEDGMENTS: We are grateful to Regina Silvia Sakae, Antonio Carlos de Souza Quaresma, and Lila Maria de Jesus da Rocha for skillful technical assistance. We are also grateful to IBM of Brazil for kindly donating the PC-AT computer used in data analysis.

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