EFFECTS OF ALTERNATING POSITIVE AND NEGATIVE ENDOTrACHEAL PRESSURES ON THE CALIBER OF BRONCHI

SEAMUS LYNN, M.D., ALBERT LEBY, M.D., KENT ELLIS, M.D.

Since the introduction of a negative phase during mechanical artificial respiration by John Hunter in 1774, there has been controversy regarding the benefits of induced active deflation of the lungs. This study was stimulated by the unexpected observation that audible wheezing could be induced during general anesthesia by the application of negative pressure to the airway during exhalation. These patients were not asthmatics and in fact had no known pulmonary disease. The apparatus used was the Stephenson Controlled Respiration Unit. The airway pressures used were sufficient to insure adequate respiratory minute volume. Tidal volume during inspiration was measured with a Monaghan ventilation meter. The expiratory wheezing was heard during a variety of surgical procedures and with various anesthetic agents including diethyl ether, cyclopropane, nitrous oxide, ethylene, succinylcholine and d-tubocurarine.

Macklin was the first to call attention to bronchial movements associated with the phases of the respiratory cycle. He demonstrated, in man, dilatation and elongation of the bronchi during inspiration and narrowing and shortening during expiration. Di Rienzo showed by bronchographic methods in the conscious patient that there was acute narrowing and closure of the bronchi, and even the trachea, during coughing. Bickerman demonstrated in dogs anesthetized with pentobarbital that there was an increase in the cross sectional diameters of the entire bronchial tree with elongation of the longitudinal axis during positive pressure inflation of the lung. A 40 mm. of mercury intratracheal pressure resulted in a 44 per cent increase in average tracheal diameter, while the primary bronchi increased 85 per cent over the normal resting level. Maximum increases over 100 per cent were observed in some smaller bronchi.

Barach noted that continuous positive pressures of 5 to 8 cm. of water applied to patients with bronchial asthma resulted in dilatation of bronchi. However, the converse, namely, that negative intratracheal pressures could produce significant degrees of bronchial narrowing has not been demonstrated. The probability of such an occurrence has been inferred as far back as 1906, by Mats who suggested that “negative airway pressures brought about collapse of the smaller bronchial tubes, not sufficiently cartilaginous and rigid to resist even moderate slow aspiration.”

Meltzer in 1914 stated that suction would favor collapse of bronchioles so that only the dead space would be ventilated. Recently it was suggested that lung compliance was reduced at volumes below the resting expiratory level when negative airway pressures were applied because such aspiration probably collapsed bronchioles. In this situation removal of even small volumes of gas would require large changes in pressure.

It was the purpose of this study to determine, under controlled conditions in human patients, the effects of alternating positive and negative airway pressures on the caliber of bronchi.

METHODS AND PROCEDURE

Five healthy female patients scheduled to undergo minor gynecological procedures were studied during thiopental, nitrous oxide-oxygen anesthesia prior to operation. Apnea was induced and maintained with succinylcholine chloride. Premedication consisted of 0.5 mg. scopolamine intramuscular 45 minutes preceding induction of anesthesia. Following respiratory paralysis the larynx was exposed and topical anesthesia of larynx and tracheobronchial tree produced by the instillation of 5 ml.
of 3 per cent Cyclaine via a tracheal cannula. Endotracheal intubation was then accomplished.

Through the vertical arm of a Rovenstone angle a no. 10 plastic catheter was introduced into the right main bronchus. Dionisol (propylidone oily suspension) was introduced through this catheter and directed to the right middle and lower lobes by placing the patient in the right Fowler position. Frontal films of the chest were taken during each respiratory cycle at a rate of two exposures per second with a Fairchild roentgenographic camera. A specially designed radio-opaque aneroid manometer recorded airway pressure for each roentgenogram exposure. Four to eight exposures were taken during each respiratory cycle.

Artificial respiration was accomplished by manual compression of the rebreathing bag and by a mechanical ventilator of the Stephenson C.R.U. type. The degree of pressure imposed on the airway was varied sequentially. Roentgenograms were taken at these pressures, summarized in Table 1.

### RESULTS

In all patients the effects of manual intermittent positive pressure respiration on bronchial caliber confirmed the observations of Bickerman et al. There was a consistent increase in cross sectional diameters proportional to the degree of applied positive pressure.

There was a consistent decrease in bronchial caliber below resting size in all patients whose exhalation phases were treated by negative airway pressure. The narrowing usually was proportional to the degree of negative pressure applied, Table 2.

The most significant change in caliber occurred in the smaller intralobular bronchi. Decreases in diameters of the trachea and main stem bronchi ranged, with the negative airway pressures used, between 7 and 19 per cent. However, smaller intralobular bronchi were reduced in caliber by 25 to 100 per cent. This significant reduction in the diameter of smaller bronchi is even more striking when one considers that a 50 per cent reduction in diameter means a 75 per cent reduction in cross sectional area and a 95 per cent increase in resistance to gas movement if there is laminar flow (Poiseuille’s Law). If flow were turbulent the resistance factor would be even greater. Since not all bronchi showed as high as a 50 per cent reduction in diameter, the over-all resistance factor was not so extreme.

The suggestions of previous investigators that intermittent negative pressure resulted in varying degrees of air trapping behind collapsed bronchioles prompted review of the bronchograms with this in mind. Conduits of bronchiolar size 0.5 mm. could not be visualized roentgenographically. In one of the 5 patients studied complete closure of a segmental bronchus was demonstrated during the negative pressure phase (see arrow fig. 1). Distal to this obstruction the bronchi supplied by this collapsed bronchus are distended (see white arrow fig. 2). There is no other evi-

### TABLE 1

<table>
<thead>
<tr>
<th>Inspiration (cm. H2O)</th>
<th>Expiration (cm. H2O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>20</td>
</tr>
<tr>
<td>Stephenson</td>
<td>15</td>
</tr>
<tr>
<td>C.R.U.</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Stephenson</td>
<td>−5</td>
</tr>
<tr>
<td>C.R.U.</td>
<td>−10</td>
</tr>
<tr>
<td></td>
<td>−10</td>
</tr>
</tbody>
</table>

of 5 per cent Cyclaine via a tracheal cannula. Endotracheal intubation was then accomplished.

Through the vertical arm of a Rovenstone angle a no. 10 plastic catheter was introduced into the right main bronchus. Dionisol (propylidone oily suspension) was introduced through this catheter and directed to the right middle and lower lobes by placing the patient in the right Fowler position. Frontal films of the chest were taken during each respiratory cycle at a rate of two exposures per second with a Fairchild roentgenographic camera. A specially designed radio-opaque aneroid manometer recorded airway pressure for each roentgenogram exposure. Four to eight exposures were taken during each respiratory cycle.

Artificial respiration was accomplished by manual compression of the rebreathing bag and by a mechanical ventilator of the Stephenson C.R.U. type. The degree of pressure imposed on the airway was varied sequentially. Roentgenograms were taken at these pressures, summarized in Table 1.

### RESULTS

In all patients the effects of manual intermittent positive pressure respiration on bronchial caliber confirmed the observations of Bickerman et al. There was a consistent increase in cross sectional diameters proportional to the degree of applied positive pressure.

There was a consistent decrease in bronchial caliber below resting size in all patients whose exhalation phases were treated by negative airway pressure. The narrowing usually was proportional to the degree of negative pressure applied, Table 2.

The most significant change in caliber occurred in the smaller intralobular bronchi. Decreases in diameters of the trachea and main stem bronchi ranged, with the negative airway pressures used, between 7 and 19 per cent. However, smaller intralobular bronchi were reduced in caliber by 25 to 100 per cent. This significant reduction in the diameter of smaller bronchi is even more striking when one considers that a 50 per cent reduction in diameter means a 75 per cent reduction in cross sectional area and a 95 per cent increase in resistance to gas movement if there is laminar flow (Poiseuille’s Law). If flow were turbulent the resistance factor would be even greater. Since not all bronchi showed as high as a 50 per cent reduction in diameter, the over-all resistance factor was not so extreme.

The suggestions of previous investigators that intermittent negative pressure resulted in varying degrees of air trapping behind collapsed bronchioles prompted review of the bronchograms with this in mind. Conduits of bronchiolar size 0.5 mm. could not be visualized roentgenographically. In one of the 5 patients studied complete closure of a segmental bronchus was demonstrated during the negative pressure phase (see arrow fig. 1). Distal to this obstruction the bronchi supplied by this collapsed bronchus are distended (see white arrow fig. 2). There is no other evi-

### TABLE 2

<table>
<thead>
<tr>
<th>Airway Pressure (cm. H2O)</th>
<th>Diameter of Bronchi (mm.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>30</td>
<td>22</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>15</td>
<td>14</td>
</tr>
</tbody>
</table>

Measurements made at identical points along bronchial tree of one patient during controlled respiration with alternating positive pressure respirations. Measurements made at peak inspiratory and expiratory pressure. Resting diameter at zero tracheal pressures shown for contrast.
Fig. 1. Bronchogram showing change in bronchial caliber during respiratory cycle. The numbers on the photographs indicate the airway pressure at the time of each exposure.

Fig. 2. Bronchogram showing apparent collapse of an intersegmental bronchus with remaining distention of the bronchi distal to this bronchus.

dence of complete closure in the remainder of this patient's right lung.

In measuring the diameters of bronchi, the possibility that bronchial rotation had occurred during respiration was considered. If this were true, measurement of an elliptical, rather than a circular tube would have been made. The fact was that certain bronchi, followed through serial roentgenograms, maintained their circular contour in spite of change in diameter, indicating that elliptical deformation of these bronchi did not occur. It is also possible that surface tension exerted by the mucoid film lining the bronchial walls exerts sufficient force to maintain the normal circular shape.

Discussion

The present study has supported the suggestions of previous investigators that negative airway pressures result in appreciable narrowing of bronchi. This narrowing is the mechanism by which audible wheezing is produced during negative pressure in the exhalation phase, because there is an increased rate of gas flow during active expiration through narrowed air conduits. Our results suggest that the application of negative pressure to the airway during controlled respiration in normal patients with the chest closed may be harmful.

The normal pressure-volume diagram of the
lungs and thorax shows a rapidly decreasing compliance as the expiratory reserve volume is entered. The curve flattens out rapidly at volumes below the resting expiratory level (fig. 3). During controlled respiration with intermittent positive pressure the tidal volume is maintained within the inspiratory capacity where compliance values are maximal. The addition of a negative phase lowers the resting expiratory level. Narrowing of the lower airway reduces the resting lung volume so that part of the tidal volume is now within the expiratory reserve volume, where the compliance is low. Such a correlation between the functional residual capacity and lung compliance has been demonstrated recently by Nisell and Du Bois in cats and in the human by Marshall. This interference in respiratory mechanics increases the inspiratory and expiratory resistance to gas flow, and leads to uneven distribution of gas to the alveoli.

Surface tension is an important factor in determining the character of the pressure-volume relationship of the lung and thorax. The force required to overcome surface tension at reduced lung volumes is considerably greater than at normal volumes, owing to the reduction in the cross sectional area of the bronchi and bronchioles. This force which tends to constrict a cylindrical tube varies inversely as the radius of the tube; therefore, small bronchioles may be completely occluded in similar fashion to the manner of the critical closure of small blood vessels. If bronchiolar closure occurs by this mechanism greater force is required to reopen them. The narrowing of the bronchial tree which occurs during application of negative pressure to the airway would seem to enhance the deleterious effects of surface tension.

These changes in mechanics of breathing deserve serious consideration during the mechanical control of respiration, when respirators incorporating a negative phase are used during clinical anesthesia. It is particularly important when a controlled pressure respirator is used since the force required to open the lung after each negative phase, may be so large that normally used pressures will not exert sufficient force to overcome the effects of increased surface tension and reduced compliance. The result may be hypoventilation. On the other hand a controlled volume respirator will be better able to supply adequate pulmonary exchange under these conditions. The use of such a respirator, however, is no guarantee that all lung units closed by negative pressure, will be reopened during each inflation phase, because inflowing gas will tend to enter and expand units offering less resistance.

**Summary**

The application of negative pressure to the airway has produced audible wheezing during controlled respiration in apneic, anesthetized patients.

Bronchographic examination of man during nitrous oxide-thiopental-succinylcholine anesthesia with controlled respiration demonstrated a significant reduction in the caliber of the intralobular bronchi during the negative pressure phase of respiration in all experiments. The degree of narrowing was approximately proportional to the degree of applied negative pressure. Narrowing of these bronchi is a plausible explanation for the audible wheezing, since there is an increased rate of gas flow during active expiration through narrowed air conduits under these conditions.

These studies offer suggestive evidence as to the reasons for reduced pulmonary compliance effected by negative pressure application to the airway.

This work was aided by a Medical Research Grant from the National Tuberculosis Association, through its Medical Section, The American Trudeau Society.
REFERENCES