Effects of smooth muscle activation on axial mechanical properties of excised canine bronchi

FELIX R. SHARDONOFSKY,1 TODD M. OFFICER,2 ALADIN M. BORIEK,2 AND JOSEPH R. RODARTE2

Departments of Pediatrics1 and Medicine,2 Baylor College of Medicine, Houston, Texas 77030

Received 30 October 2000; accepted in final form 6 November 2000

Shardonofsky, Felix R., Todd M. Officer, Aladin M. Boriek, and Joseph R. Rodarte. Effects of smooth muscle activation on axial mechanical properties of excised canine bronchi. J Appl Physiol 90: 1258–1266, 2001.—This study tested the hypothesis that airway smooth muscle (ASM) activation produces an airway active axial force (AAAF). Bronchi (n = 10) immersed in a tissue bath containing 95% O2-5% CO2-equilibrated Krebs solution were subjected to passive axial lengthening and shortening at 0–20 cmH2O of transmural pressure. ASM was relaxed with isoproterenol and activated with methacholine. Axial tension (ex), transverse compressive (ey), and shear strains (exy) were computed from the displacements of four markers placed onto the specimen’s surface. The AAAF was estimated by subtracting the control axial force (AF) values at a given ex from those obtained after methacholine. ex-AF relationships were curvilinear, with maximum ex being approached at ~15 g of AF. The ey decreased during bronchial lengthening. Cholinergic stimulation produced 1) a decrease of both ex and ey at a given AF relative to control, indicating ASM shortening, and 2) an AAAF that increased with increasing ex and transmural pressure. A portion of the work of expanding the lungs is required to lengthen the airways; therefore, an AAAF would increase lung elastance and recoil.

elastance; compliance; lung recoil; bronchoconstriction; pulmonary mechanics

AIRWAY RESISTANCE, dynamic and static elastance, and static lung elastic recoil pressure are increased or decreased with vagus nerve stimulation or cholinergic blockade, respectively (5, 8, 27, 38). Changes in airway resistance elicited by cholinergic modulation are attributed to changes of airway diameter associated with variations of airway smooth muscle (ASM) activation, but the mechanisms for cholinergic-mediated changes in lung elastic recoil are incompletely understood. The lung elastic recoil pressure reflects the stress in the connective tissue fibers in the lung parenchyma and the surface tension in the gas-liquid interface (37). The active lung recoil, i.e., the component of recoil pressure that varies in response to smooth muscle-constricting or muscle-relaxant stimuli, is likely a consequence of complex interactions between pulmonary passive mechanical elements and an array of contractile cells whose identities remain to be elucidated.

Experimental data indicate that smooth muscle cells in conducting airways influence lung elasticity. The efferent cholinergic innervation in the lung is mainly distributed to conductive airways (23, 29), which makes it likely that variations of lung recoil in response to vagus nerve stimulation or cholinergic blockade are related to changes of ASM activation. This possibility is further supported by data reported by Mitzner et al. (27), who have shown that delivery of a cholinergic agonist into the bronchial circulation of sheep increases lung elastance and pulmonary resistance, whereas pulmonary mechanics does not change when the same dose of agonist was delivered into the pulmonary circulation. In addition, the volume density of ASM cells in the lung appears to be sufficient for ASM contraction to cause an increase in lung recoil pressure of a magnitude similar to that observed during administration of contractile agonists in dogs (1, 37). ASM activation-related changes in lung elasticity can be brought about by several mechanisms. As a result of a helixlike pattern arrangement of ASM cells in bronchi (24), ASM contraction is expected to produce active forces in both the circumferential and axial directions of the airway (2). Active bronchial circumferential forces decrease the outer airway diameter, deforming the lung parenchyma attached to the outer surface of the airway and increasing the lung recoil. This is proportional to the magnitude of the parenchymal deformation and the value of the shear modulus of the lung parenchyma (33, 37). Active forces in the axial direction of the airways would increase lung recoil pressure and pulmonary elastance because a proportion of the work of expanding the lung is required to lengthen the airways (35, 37). In addition, a shift of gas volume between constricted airways and alveoli would cause a negligible increase of lung recoil pressure (37). Although previous studies have suggested that ASM contraction alters the axial bronchial mechanical properties of excised bronchi (28) and affects lung expansion (7), the effects of ASM activation on axial bronchial mechanical properties have not been carefully

Address for reprint requests and other correspondence: F. R. Shardonofsky, Baylor College of Medicine, Texas Children’s Hospital, Section of Pediatric Pulmonology, 6621 Fannin, MC 3-2571, Houston, TX 77030-2399 (E-mail: felix@bcm.tmc.edu).

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.
examined. The purpose of this study was to test the hypothesis that activation of ASM produces an active force in the axial direction of the bronchial tree.

METHODS

Specimens. Mongrel dogs were killed with an overdose of pentobarbital sodium, and their left diaphragmatic lobes were removed and immersed in 95% O2-5% CO2-equilibrated Krebs solution of the following composition (in mM): 110 NaCl, 3.4 KCl, 2.4 CaCl2, 0.8 MgSO4, 25.8 NaHCO3, 1.2 KH2PO4, and 5.6 glucose. Cartilaginous intraparenchymal bronchi pertaining to the fourth or fifth bronchial generation were dissected free from parenchymal tissue, and their side branches were tied off to form an airtight tube. Eighteen specimens were studied; data from eight bronchi were of poor quality and discarded. The mean ± SD length and thickness of the unstressed bronchi measured with a caliper were 16 ± 1 and 1.2 ± 0.2 mm, respectively. The experiments described in this report were approved by the Animal Research Ethics Board of Baylor College of Medicine.

Experimental equipment. Specimens were immersed in a 250-ml Plexiglas organ chamber containing 95% O2-5% CO2-equilibrated Krebs solution at room temperature. Each bronchus was coupled to a testing system by inserting a rigid plastic cannula of outside diameter similar to the bronchial axial length to be made by applying tensile or compressive forces homogeneously over the circumference of the two opposite bronchial ends. A force transducer (World Precision Instrument, model FORT 250, ±250 g, differential bridge type) was attached to one of the plastic cannulas. The transducer was mounted on a linear ball carriage (Ball Slide) with a right-hand threaded shaft (Reed Tools). Owing to the force transducer was a plastic cannula connected to the opposite end of the specimen, which was attached to a vertical metal rod mounted on a ball carriage with a left-hand threaded shaft. The left- and right-threaded shafts were coupled together in the center of the apparatus as described by Humphrey et al. (17). A micrometer or a stepper motor (Applied Motion Products) with a 0.24° step was connected to one end of the right-hand shaft. The stepper motor was driven by a custom-built circuit using a Motorola driver (SAA 1042). When the shaft was rotated in the clockwise direction, the separation between the two opposing cannulas decreased; when the shaft was rotated in the counterclockwise direction, the separation increased. One of the plastic cannulas was connected via a thick-walled Silastic tubing to both a column containing Krebs solution and a calibrated Celesco differential pressure transducer (±100 cmH2O). The level of the fluid column could be varied to change the bronchial transmural pressure (Ptm). In addition, the fluid column provided a pressure sink to keep Ptm essentially constant during passive lengthening and shortening of the bronchus. The bronchus, attached cannulas, connecting tubing, and pressure transducers were filled with Krebs solution. Before each study, the experimental apparatus was tested for leaks.

The axial force (AF) and Ptm signals were amplified, filtered at 5 Hz (902LPF 8 pole, Frequency Devices, Haverhill, MA), sampled at 10 Hz with a 12-bit analog-to-digital converter (Data Translation 2801-A, Marlborough, MA), and stored in a personal computer (Dell 5133, Austin, TX). Data collection and analysis were carried out with the ANADAT-LABDAT software package (RHT-InfoDat, Montreal, Quebec, Canada). The sampling frequency of the AF signal, which was digitally recorded at 10 Hz, was decreased to 2 Hz, which was the same as that used to digitally capture the bronchial imaging data.

Measurement of bronchial strains. The deformation of the bronchi during passive lengthening and shortening was assessed by monitoring the displacements of four markers placed ≈1 mm apart onto the surface of the central portion of the specimens, forming a roughly square target. The markers consisted of silk threads (7-0, Surgiline) sutured through the adventitia of the bronchi. To define a boundary as homogeneous as possible in excised bronchi, which are composite structures of branching geometry, care was taken to avoid suturing the silk markers over a cartilaginous plate or placing them at branching sites. Bronchi were mounted horizontally just beneath the surface of Krebs solution, with the markers facing upward, allowing the markers’ position to be recorded on video cassette (SONY SLV-620HF) using a CCTV video camera at Hachi, HY-7200. The recorded video was digitally captured off line, using a frame grabber (Captivator PC, VideoLogic) at a sampling rate of 2 Hz. Markers were digitized, and markers’ positions were determined in Cartesian coordinate axes using the Image tool V2.0 program (36), assuming that all markers lay on the same plane field. The coordinates of these points in the plane at the reference position were denoted xi and yi (i = 1, 2, 3, 4). The reference markers’ positions (xi′, yi′) were those obtained after isoproterenol-induced ASM relaxation and preconditioning of the specimens at an AF of 0–1.0 g and a Ptm of 5 cmH2O. During passive lengthening and shortening of the bronchi, the displacements of the markers from their reference positions were determined and denoted u and v, with ui and vi being equal to (xi − xi′) and (yi − yi′), respectively. In the displacement field, ui and vi were assumed to be a linear function of their position, as described by the following relationship

\[ u_i = a_1 + a_2 x_i + a_3 y_i \]  

(1)

Coefficients a1, a2, and a3 in Eq. 1 were estimated by multiple linear regression analysis using the measured values for all markers’ displacements and position. Similarly, the data provided the information required to determine the coefficients in the following equation

\[ v_i = a_4 + a_5 x_i + a_6 y_i \]  

(2)

The coefficient a2 in Eq. 1 reflected the fractional change of axial length (δu/δx) or ex, and the coefficient a3 in Eq. 2 indicated the fractional change of outer airway diameter (δa/δy) or transverse compressive strain (εy). The coefficient a5 in Eq. 1 and the coefficient a6 in Eq. 2 reflected axial displacement per unit of transverse displacement (δu/δy) and transverse displacement per unit of axial displacement (δu/ δx), respectively. The shear strain (εxy) was computed as follows (34)

\[ \epsilon_{xy} = 0.5(\delta u/\delta y + \delta u/\delta x) \]  

(3)

Experimental protocol. Specimens were allowed to equilibrate in the organ chamber for ≈60 min, during which the Krebs solution was changed at least twice. To ensure that the data obtained in the control state reflected the passive mechanical properties of bronchial tissues, ASM relaxation was induced by adding l-isoproterenol (10−4 M bath concentration) (Sigma Chemical, St. Louis, MO) to the organ bath at the end of the equilibration period. The relaxed bronchi were preconditioned by stretching them 8–10 times to an AF of 30 g. Bronchi were then unloaded to an AF of 0 ± 1 g. In the
control state, AF and markers’ positions were recorded during passive lengthening and shortening of the bronchi while specimens were held at constant Ptm. Data were obtained at Ptm values of 0, 3, 5, 10, and 20 cmH$_2$O, with the sequence of pressures at which the bronchi were subjected being randomly chosen. The duration of lengthening and shortening cycles ranged from 22 to 25 s, during which the AF ranged from 0 to ~50 g. After completion of data collection under baseline conditions, specimens were washed several times with Krebs solution, and ASM activation was induced by adding methacholine (MCh; 10$^{-3}$ M bath concentration; Sigma Chemical) to the organ bath. Two runs were performed at each Ptm in the control state and during MCh treatment. For each experimental condition, data pertaining to the second run are reported.

Statistical analysis. Comparisons among experimental conditions were performed using one-way analysis of variance and covariance. When a significant difference was found, the Bonferroni test was performed to determine significant differences between different experimental conditions. A P value <0.05 was accepted as statistically significant. The relationships among airway active axial force (AAAF) and $\varepsilon$ were expressed as percentage of peak $\varepsilon$ at a Ptm of 5 cmH$_2$O (ex%) and Ptm were examined using the following model:

$$\text{AAAF} = \alpha \varepsilon + \beta \text{Ptm} + \gamma \varepsilon \% \text{Ptm} + \varepsilon \%^2 + \mu \text{Ptm}^2$$  (4)

The statistical analysis was performed using the SPSS statistical package (SSPS, Chicago, IL). Values are means ± SE unless otherwise specified.

RESULTS

Bronchial active AF. Cholinergic stimulation of ASM produced a measurable airway AF, as shown by representative AF-vs.-time tracings obtained in an excised bronchus kept at constant length and a Ptm of 5 cmH$_2$O (Fig. 1).

Axial mechanical properties of excised bronchi during passive length changes. Figure 2A illustrates $\varepsilon$-AF relationships obtained during passive lengthening and shortening of a bronchus kept at 5 cmH$_2$O of Ptm in the control state and during MCh treatment. $\varepsilon$-AF relationships were curvilinear, with a maximum degree of extensibility ($\varepsilon_{\text{peak}}$) being approached at an AF of ~15 g. Compared with control, cholinergic stimulation decreased the bronchial length ($\varepsilon$) at any given AF value during passive bronchial lengthening. At a Ptm of 5 cmH$_2$O, the values for $\varepsilon_{\text{peak}}$ fell from 0.30 ± 0.07 under control conditions to 0.24 ± 0.07 during cholinergic stimulation ($P < 0.01$), reflecting bronchial axial shortening associated with ASM contraction. At a given $\varepsilon$ value, the difference of AF obtained during MCh and that obtained in the control state measured the magnitude of the AF developed by activated ASM cells. In the example shown in Fig. 2A, the $\varepsilon$-AF relationships obtained during passive shortening of the specimens under control conditions and during ASM contraction were similar, indicating a marked decrease of active force generation after smooth muscle stretch. The differences of AF values measured at 50% $\varepsilon_{\text{peak}}$ between passive bronchial lengthening and shortening, which reflects the magnitude of $\varepsilon$-AF hysteresis, increased from 0.39 ± 0.20 g in the control state to 1.52 ± 0.19 g during MCh treatment ($P < 0.01$).

Effects of Ptm on $\varepsilon$-AF relationships. To examine the effects of Ptm on the axial mechanical properties of excised bronchi, $\varepsilon$-AF curves obtained on passive lengthening were fitted to the following exponential function: $\varepsilon = A + B \cdot e^{CAF}$, where $A$, $B$, and $C$ are constants and AF is axial force. The $\varepsilon$-AF relationships obtained on passive shortening at AFs ≤8 g were better described by a third-order polynomial function: $\varepsilon = a + bAF + cAF^2 + dAF^3$, where $a$, $b$, $c$, and $d$ are constants. This equation was used for analysis of $\varepsilon$-AF relationships obtained during passive shortening of the bronchi. To compare $\varepsilon$-AF relationships among bronchi exhibiting different $\varepsilon_{\text{peak}}$, the $\varepsilon$ values obtained under different experimental conditions for each specimen were expressed as percentage of the $\varepsilon_{\text{peak}}$ value obtained at Ptm of 5 cmH$_2$O ($\varepsilon \%$).

In the control state between 0 and 8 g of AF, the change of bronchial axial length per unit AF was
During cholinergic stimulation, the mean $\epsilon_x\%$ values within the AF range studied were decreased relative to those obtained in control conditions and similar Ptm. The values of $\epsilon_x\%$ obtained during MCh treatment at AF $\geq$ 4 g and at Ptm $\geq$ 5 cmH$_2$O were significantly lower ($P < 0.05$) than the corresponding control values of $\epsilon_x\%$ (Fig. 3). In addition, the average $\epsilon_x\%$ values obtained during cholinergic stimulation at an AF of 0 g were not affected by increasing Ptm, likely reflecting an increased bronchial stiffness associated with ASM activation.

Effects of passive length changes and Ptm on AAAF. By subtracting the AF values at isoleth (iso-$\epsilon_x\%$) points on the passive $\epsilon_x\%$-AF relationships obtained under control conditions from those obtained during MCh treatment, the values of AAAF as a function of bronchial length ($\epsilon_x\%$) were computed. A stepwise multiple linear regression analysis using the model described by Eq. 4 indicated that the values of AAAF were significantly correlated with bronchial length and Ptm ($R^2 = 0.89$) (Table 1). These relationships are illustrated in Fig. 4, in which the surface representing AAAF as a function of bronchial length and Ptm was derived from the coefficients shown in Table 1. The magnitude of AAAF was enhanced with passive increases of bronchial axial length and Ptm. The values for AAAF during passive bronchial shortening (Fig. 4B) were lower than those during passive bronchial lengthening (Fig. 4A), reflecting a decrease in both stiffness and force generation after ASM stretching.

Effects of passive bronchial lengthening on $\epsilon_y$. In the control conditions at constant Ptm, the magnitude of $\epsilon_y$ decreased during passive lengthening of the specimens (Fig. 2B, Fig. 5), indicating a decrease in outer airway diameter. Transverse compressive strains occurred during passive bronchial lengthening. The average values for $\epsilon_y$ increased, i.e., the outer airway diameter was enhanced with increasing Ptm. Compared with control, the values for $\epsilon_y$ obtained during cholinergic stimulation at any value of AF and at Ptm $>0$ cmH$_2$O were significantly decreased ($P < 0.05$), indicating bronchial narrowing due to a transverse compressive force generated during ASM contraction (Fig. 2B, Fig. 5).

Effects of passive bronchial lengthening on $\epsilon_z$. Both in the control state and during MCh treatment, passive lengthening of bronchi was associated with small $\epsilon_z$ (data not shown). No differences in the magnitude of $\epsilon_z$s were observed between the control state and during ASM activation.

**DISCUSSION**

This study demonstrates that activated ASM cells produce a decrease of axial bronchial length and a force in the axial direction of the airway whose magnitude is enhanced with increases of bronchial length and Ptm. The contraction of ASM cells also produces a circumferential compressive force that causes bronchial narrowing. This has long been recognized. The validity of these results rests on the accuracy of the computed strains. To measure the deformation of excised canine
bronchi produced by passive changes of axial length, Ptms, and cholinergic-induced ASM activation, strains were calculated from the displacements of four markers placed onto the central portion of the specimens, away from the local distortion produced by the attached cannulas. The geometry of the displacement field was treated as a plane because the transverse distance among markers was small. Excised bronchi were assumed to be homogeneous, incompressible cylinders. The \( \varepsilon_x \) described fractional changes of bronchial length. The \( \varepsilon_y \) depicted fractional changes of cord distances among markers, which reflected fractional changes of outer bronchial diameter. The small \( \varepsilon_y \) during passive bronchial lengthening indicated that significant changes of shape of the testing field did not occur.

The reference configuration chosen to compute strains was that of isoproterenol-relaxed bronchi, kept at an AF of 0–1 g and a Ptms of 5 cmH\(_2\)O. The latter was similar to the Ptms in intact canine bronchi at functional residual capacity. The value of AF taken to define the reference configuration was probably close to the AFs exerted on bronchi in situ at low lung volume. The observation that excised canine bronchi subjected to a Ptms of 0 cmH\(_2\)O and an AF of 0 g are shorter by 5% (18) or 15% (14) relative to their in situ lengths indicates that intact bronchi are likely subjected to tensile AFs rather than compressive AFs. This is further supported by experimental data indicating that a Ptms of 3 cmH\(_2\)O or a tensile force of 1 g restores the length of canine excised bronchi to values similar to those in the intact lung expanded at a transpulmonary pressure (P\(_{L}\)) of 3 cmH\(_2\)O (19) or 10 cmH\(_2\)O (11), respectively. Moreover, Wilson (37) has estimated that, in a uniformly expanded lung kept at a P\(_{L}\) of 5 cmH\(_2\)O, the AF exerted on a hypothetical airway of 5 mm outside diameter and 0.2 cm\(^2\) of wall cross-sectional area (A) equals P\(_{L}\)\(\times\)A or 1 g.

The curvilinear behavior of the \( \varepsilon_x\)-AF relationships of excised bronchi is consistent with data previously published (6, 25, 28, 30). The average \( \varepsilon_x \) of relaxed bronchi kept at 0 cmH\(_2\)O of Ptms varied from \(-0.08\) to \(-0.29\) when AF was raised from 0 to 15 g. These \( \varepsilon_x \) changes are comparable to those obtained in free hanging canine bronchi by Marshall (25). Croteau and Cook (6) have reported axial length-AF relationships of second-generation bronchi procured at autopsy from human subjects aged 4–11 yr. Those human bronchi attained a maximum degree of extensibility (\( \varepsilon_{xpeak} \))

### Table 1. Results of stepwise multiple linear regression analysis among active axial airway force, axial strain, and transmural pressure during passive lengthening and shortening of excised bronchi

<table>
<thead>
<tr>
<th>Model Predictors</th>
<th>( R^2 )</th>
<th>Coefficient</th>
<th>Standard Error</th>
<th>t</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Passive bronchial lengthening</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>0.89</td>
<td>0.867</td>
<td>0.331</td>
<td>2.62</td>
<td>0.013</td>
</tr>
<tr>
<td>( \varepsilon_x% )</td>
<td></td>
<td>-0.045</td>
<td>0.016</td>
<td>2.87</td>
<td>0.007</td>
</tr>
<tr>
<td>Ptms</td>
<td></td>
<td>0.173</td>
<td>0.020</td>
<td>8.76</td>
<td>0.000</td>
</tr>
<tr>
<td>( \varepsilon_x%^2 )</td>
<td></td>
<td>0.001</td>
<td>0.000</td>
<td>6.40</td>
<td>0.000</td>
</tr>
<tr>
<td><strong>Passive bronchial shortening</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>0.91</td>
<td>0.258</td>
<td>0.108</td>
<td>2.39</td>
<td>0.023</td>
</tr>
<tr>
<td>Ptms</td>
<td></td>
<td>0.085</td>
<td>0.029</td>
<td>2.93</td>
<td>0.006</td>
</tr>
<tr>
<td>Ptms-( \varepsilon_x%^2 )</td>
<td></td>
<td>0.001</td>
<td>0.000</td>
<td>2.09</td>
<td>0.044</td>
</tr>
<tr>
<td>Ptms(^2)</td>
<td></td>
<td>-0.003</td>
<td>0.002</td>
<td>2.13</td>
<td>0.041</td>
</tr>
<tr>
<td>( \varepsilon_x%^2 )</td>
<td></td>
<td>0.000</td>
<td>0.000</td>
<td>5.34</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Stepwise multiple linear regression analysis was performed by using the model shown in Eq. 4. \( \varepsilon_x\% \), Axial strain as percentage of axial strain values obtained in isoproterenol-relaxed bronchi, subjected at an axial force of 15 g and a transmural pressure of 5 cmH\(_2\)O; Ptms, transmural pressure; t, coefficient/standard error.
similar to that shown in our specimens, with the AF at $\varepsilon_{\text{peak}}$ being 10-fold greater than that observed in the present investigation. In the bronchi studied by Crouteau and Cook, an elevated AF at $\varepsilon_{\text{peak}}$ could be due to the presence of ASM tone in autopsy specimens that were not kept immersed in an organ bath. Furthermore, those bronchi were neither subjected to preconditioning nor treated with relaxant agonists.

The axial length of isoproterenol-relaxed bronchi was dependent on both AF and Ptm. The change of $\varepsilon_x$ per unit AF was decreased when Ptm was enhanced (Fig. 3). On the other hand, the linear increase of $\varepsilon_x$ with Ptm in bronchi not subjected to AF vanished as AF was increased (Fig. 3) (25, 32). Taken together, these data indicate that passive increases of bronchial axial length and Ptm, which occur during lung inflation, make bronchi axially stiffer.

Whereas the decrease of the outer bronchial diameter with passive lengthening (Fig. 5) is in agreement with previous studies in excised dog (32) and human bronchi (19), it is in marked contrast with the increases in both diameter and length of intact bronchi with lung expansion (16, 18). Bronchi in situ are subjected to a progressive increase of both Ptm and forces of airway-parenchymal interdependence (26) during increasing lung volume.

Our results confirmed the notion that activated ASM cells bring about forces in both the circumferential and
axial directions of the bronchi (Figs. 1–4) (2). These forces result from the contraction of smooth muscle bundles helically arranged within the bronchial wall (2, 24). The observed increase of bronchial active AF when the specimens were stimulated at increasing Ptm and axial length (Fig. 4) is consistent with previously reported “in vitro” studies showing that the Ptm developed by excised bronchi during isovolumetric contractions is augmented at increasing bronchial volume (12). Furthermore, “in vivo” studies have shown that the active lung recoil pressure in dogs is enhanced in response to an increase in the level of positive end-expiratory pressure (1). The dependency of AAAF on both Ptm and axial length could be accounted for by a variation in the angle of orientation of ASM bundles associated with passive bronchial lengthening and length-related changes of active force. The mechanisms explaining length-dependent changes of active force have been recently reviewed by Gunst and Tang (13). They include mechanical interactions between adjacent cells, length-dependent changes in the activation of contractile filaments, and mechanosensitive alterations in the organization or length of the contractile filaments.

The magnitude of AAAF during passive bronchial shortening was smaller than that during bronchial lengthening. Similar length history-dependent changes of active force have been reported in actively contracted trachealis muscle and bronchial smooth muscle subjected to length or bronchial volume oscillations (12, 31). A depressed contractility during passive muscle shortening could be due to plasticity of the cellular organization of contractile filaments within smooth muscle cells. It has been hypothesized that the contractile element length could be reset and/or the number of actin-myosin interactions could be altered in response to smooth muscle stretch (10).

The magnitude of active force developed by contracted smooth muscle cells subjected to length oscillations has been shown to be strongly influenced by the amplitude and rate of length changes (31). Thus the magnitude of AAAFs obtained in our specimens may not reflect those produced by the same specimens under physiological conditions because the amplitude and rate of axial length changes imposed on the studied bronchi were different from those during spontaneous tidal breathing in dogs.

**Implications.** Airways in situ change length in proportion to the cubic root of lung volume (VL1/3) (16, 32). Unfortunately, we could not relate changes of bronchial length to Ptm of intact and excised airways. A comparison between average axial length-Ptm (ex-Ptm) relationships of excised canine bronchi. The VL1/3-PL relationship depicted by a continuous line was derived from a lung volume-PL characteristic of a canine lung previously published (15). The average ex-Ptm relationships of excised bronchi were obtained at an AF of 0 g in isoproterenol-relaxed bronchi (23) and during cholinergic stimulation (8). Values for ex and VL1/3 were expressed as percentage of the corresponding values obtained at pressures of 5 cmH2O.

![Graph](http://jap.physiology.org/)

Fig. 6. Comparison between the cubic root of lung volume (VL1/3)-transpulmonary pressure (Pt) and average axial length-Ptm (ex-Ptm) relationships of excised canine bronchi. The VL1/3-PL relationship depicted by a continuous line was derived from a lung volume-PL characteristic of a canine lung previously published (15). The average ex-Ptm relationships of excised bronchi were obtained at an AF of 0 g in isoproterenol-relaxed bronchi (23) and during cholinergic stimulation (8). Values for ex and VL1/3 were expressed as percentage of the corresponding values obtained at pressures of 5 cmH2O.

This indicates that, for the excised bronchial tree, the increase of bronchial segment length with Ptm is less than the increase of bronchial segment length with PL with the bronchial tree in situ. The matched expansion of intact airways and lung parenchyma has been attributed to shear stresses at the airway-parenchymal boundary, which produce an AF on the airways (20). During ASM activation, bronchial lengths are less than VL1/3 and change less with pressure than VL1/3. These data are in line with the notion that, during ASM activation, the axial contraction and stiffening of the bronchi contribute to the active lung recoil (37) and limit lung expansion (7). However, without better knowledge of the volume at which in situ and in vitro lengths are matched, it is not possible to quantitate the magnitude of these effects.

The mechanisms by which changes of bronchial axial mechanical properties alter lung recoil are not well understood. Wilson (37) has suggested that the axial contraction of the airways would accumulate along the bronchial tree. Thus small fractional length changes would produce large displacements along the airway and severe parenchymal distortion. AAAFs should be associated with opposite forces developed by parenchymal elements and shear forces on the surface of the airways that prevent the airway from shortening. The nature of the parenchymal elements is unknown. The connective tissue skeleton of the lung is an interconnected structure (35), and the intersegmental septa that connect the pleural membrane with the airways provide the forces that extend the intact bronchial tree. It is conceivable that the axial contraction of the airways increases the tension in the connective tissue and increases lung recoil (37). An additional mechanism by
which the ASM activation increases the lung recoil is related to the lung tissue distortion due to a decrease in outer airway diameter. The magnitude of this contribution to active recoil has been estimated to be ~5% of Pt (37).

ASM contraction is not the only source of active recoil. The activation of lung parenchymal contractile cells, including smooth muscle cells located in alveolar ducts (4), bronchioli and blood vessels, and myofibroblasts in alveolar septa and pericytes (21, 22), have been suggested to contribute to active recoil. Indeed, lung parenchyma strips immersed in an organ bath and subjected to cyclic length changes show active tissue tension as well as enhanced stiffness, hysteresis, and resistance when they are stimulated with contractile agonists (9). However, the volume density of parenchymal contractile cells has been estimated to be insufficient for these cells’ activation to produce an active recoil pressure in the order of 1–3 cmH2O reported in the literature (1, 37). It has been hypothesized that, because alveolar ducts and alveolar septa are arranged mechanically in series (4), contraction of smooth muscle cells in alveolar ducts would expand the alveolar surface area, thereby increasing the surface tension and elastic recoil. This hypothesis seems to be untenable because the contractile stimulation of saline-filled lungs, in which the air–liquid interface is abolished, causes an increase in elastic recoil of a magnitude similar to that obtained in air-filled lungs (3, 37).

In conclusion, the results of this study demonstrate that activated ASM cells produce axial shortening of excised bronchi and a force in the axial direction of the airways, in addition to a circumferential compressive force. The active airway AF, which increases with increasing Ptm and bronchial length, likely contributes to the active lung recoil pressure.

We thank Theodore A. Wilson for insightful critiques.

F. R. Shardonofsky was supported by National Heart, Lung, and Blood Institute grant HL-03784 and by The American Lung Association of Texas.

REFERENCES


