Lung Area from Surface Tension Effects. (23155)

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A method for estimating the internal surface area of the lungs was recently presented by Radford which depends upon the thermodynamic properties of the surface(1). The free energy change in the lungs can be calculated from the static pressure-volume relationships during deflation. This change in free energy results from dissipation of surface free energy and elastic free energy as the volume decreases. When the lung is filled with and immersed in saline, the surface free energy is minimized because interfacial tension is small compared to surface tension. Therefore, the difference in the free energy between deflation in air and deflation in saline represents surface free energy. The elastic energy is assumed to be unchanged on passing from air to saline. Since the change in surface free energy is a product of surface tension and change in surface area, when 2 of these quantities are known the third can be computed. Unfortunately, 2 of these quantities are unknown, namely the surface tension and the change in area.

In his computations Radford assumed that the surface tension would be approximately that of serum, 50 dynes per cm. This assumes that the fluid on the lung surface is a pure transudate of the blood fluids. The surface area computed on this basis at functional residual capacity (FRC) was 5-10 m^2 for man. The discrepancy between this estimate and the histologic estimates of Willson(2) and Gertz(3) was attributed by Radford to distortion in fixation and errors in assuming a total lung volume. These factors when applied to the histologic estimates would produce values in the range of 7-20 m^2. Extracts of lung tissue were studied by von Neergaard (4) who obtained surface tensions of 35 to 41 dynes per cm. On the other hand, Pattle, on the basis of stability of bubbles expressed into air saturated saline from cut lung surfaces, concluded that lung surface tension approached zero(5). His view is probably somewhat extreme, since insoluble surface films hinder the transfer of materials across surfaces. Pattle demonstrated such a surface film, probably mucoprotein in nature, by staining of the stable bubbles. He produced similar stable bubbles from nasal and gastric mucus but not from blood, amniotic fluid or tracheal mucus. Because the surface tension decreases during compression of a protein film, both von Neergaard and Pattle could be correct; von Neergaard measuring the expanded film, and Pattle the maximally compressed film. This report presents evidence that such is indeed the case.

Results. The surface tension of nasal mucus films was 40-50 dynes per cm by the capillary tube method. A crude indication of the effects of compression was obtained by measuring the static pressure and volume in bubbles blown from nasal mucus, allowed to stand 15-30 minutes, and deflated by stages. Surface area was computed from volume and surface tension from pressure and volume. A marked decrease in surface tension was observed on deflation, reaching a limiting value of about 17 dynes per cm (Fig. 1). The minimum coefficient of compressibility or ratio of change in log of area to change in surface tension was 0.016 cm/dyne. Similar studies on human pulmonary edema fluid indicated a limiting value of 5-10 dynes/cm and when expanded 40-50 dynes/cm. This material, however, was not fresh when tested.

An *in vivo* deflation of the lungs of rats, cats and dogs provided pressure-volume relationships for calculation of lung surface tension. The tracheotomized animal whose pleural cavities were widely exposed was placed in a plethysmograph and respired with oxygen. After denitrogenation, the airway was clamped, and airway pressure and plethysmograph volume were recorded until apparently all gas had been removed from the lungs. Subsequently saline inflation and deflation were carried out on the degassed lung.

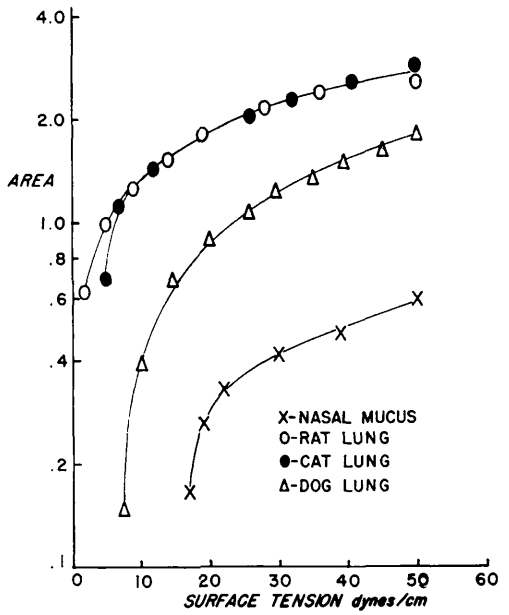

FIG. 1. Alteration of surface tension with change in area. Ordinate axis units: nasal mucus—cm^2; rat—.1 m^2; cat—1 m^2; dog—10 m^2.

The pressure-volume curves obtained by this procedure were similar to those obtained by von Neergaard and by Radford. The saline deflation curves were extrapolated to zero volume since complete emptying was not effected. The differential pressure at the end of air deflation was −1.5 to −5 cm of water. Little or no change in rate of oxygen uptake was observed during the course of deflation. However, cardiac output was not measured, so changes in oxygen transfer coefficient could not be noted.

A lung volume was selected which was near full inflation but still in the linear region of the pressure-volume curve. The surface tension after inflation to this volume was assigned a value of 50 dynes/cm for purposes of computation. A small deflation from this volume was assumed to decrease all spatial coordinates of the lung units proportionately and, hence, that surface area was proportional to volume to the two-thirds power. From the free energy change appearing as the area between the air and saline curves and the assigned surface tension, the change in surface area was calculated. The total surface area was computed using the assumed proportionality between surface area and volume to the two-thirds power. From this area, areas at other volumes were calculated from this proportionality.

The surface tensions relative to the assumed 50 dynes/cm value were calculated at other volumes from the free energy change and the change in calculated area. The relative surface tension in rat, cat, and dog lungs decreased rapidly with deflation (Fig. 1). The limiting value for relative surface tension was 5 to 10 dynes per cm. The minimum coefficients of compressibility ranged from 0.012 to 0.020 cm/dyne as compared to 0.016 cm/dyne for nasal mucus.

While absolute values cannot be assigned to the surface tension at a particular lung volume, the surface tension in the expanded lung probably is not smaller than the 35 to 41 dynes per cm found by von Neergaard. The lower limit is in doubt because of extrapolation of the saline pressure-volume curves but probably is not zero. Intermediate values should obtain at functional residual capacity and a small oscillation in surface tension probably occurs with quiet breathing. Because rate of oxygen uptake remained essentially constant during deflation, resistance of the lung surface film to oxygen transfer is probably not limiting except when severely compressed.

The lung surface areas at functional residual capacity calculated for rats, cats and dogs were linearly related to body weight. Extrapolation to a body weight of 70 kg indicated a surface area of 70 square meters for man. A simple computation of mean diameter of a lung unit was made by assuming these units to be hemispherical. The mean diameter is 6 times the volume to area ratio. These mean diameters (Table I) were approximately twice those found by Macklin and Hartroft(6). A further calculation using the diameters of Macklin and Hartroft gave the number of "lung units" required to yield the calculated surface area.

The aggregate picture of the human lung as developed in these computations is in good accord with previous histologic estimates. A surface area of 70 m^2 at a functional residual

TABLE I. Lung Surface Area and Alveolar Parameters in Several Species.

	Wt (kg)	FRC (cc)	Area (m^2)	Dia. alv. (calc.), μ	Dia. alv. (obs.*), μ	No. of alv. (millions)
Rat	.2	5	.18	167	60	8.0
Cat	2.	100	2.075	290	130	19.5
Dog	10.	400	10.3	230	75	290.
Man	70.	2250	70.	190	150†	500.

* From Macklin and Hartroft(6). † Recalculated for 2250 cc lung vol.

capacity of 2250 cc is associated with an alveolar volume of 1750 cc comprising about 80% of the total volume. The number of alveoli is 500 million and—from Macklin and Hartroft—their mean diameter is 150 μ. The surface film has a surface tension of 20-25 dynes/cm. The surface tension rises to 40-50 dynes/cm on maximum inspiration and falls to 15-20 dynes/cm on expiration to residual volume.

Summary. The surface tension of pulmonary edema fluid was 5-10 dynes/cm as measured in aged, compressed bubbles; it was 40-50 dynes/cm as measured by capillary tube. Nasal mucus on aging and compression exhibits a fall of surface tension from 45-50 dynes/cm to 17 dynes cm with a minimum compressibility coefficient of 0.016 cm per dyne. Calculations of relative surface tension in lungs of rats, cats and dogs assuming 50 dynes/cm for the upper limit showed a fall to 5-10 dynes/cm during deflation with minimum compressibility coefficient of 0.012 to 0.020 cm/dyne. The lung surface areas calculated for these species were proportional to body weight and extrapolated to 70 m^2 for a 70 kg man.

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Surface Tension of Lung Extracts. (23156)

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Von Neergaard described the important role played by surface forces in the recoil of the lungs and made measurements of surface tension in lung extracts(1). Recently, Radford and his coworkers repeated and extended von Neergaard's experiments, again calling attention to the importance of surface tension in the static pressure-volume characteristics of the lungs(2) and pointing out the need for proper determination of the surface tension of the lung lining. In the interim Radford used the so-called static tension of serum (50 dynes/cm) in interpreting his results, assuming the surface to be thermodynamically reversible. From microscopic study of air bubbles squeezed from lung slices Pattle(3) concluded that the pulmonary alveoli are lined with mucoprotein (suggested previously on the basis of histochemical evidence by Macklin(4)) and that this material reduced the surface tension to less than 1 dyne per cm. In the last year Brown(8) repeated Radford's experiments and by assuming the lung to be composed of many identical hemispherical units computed surface tension from the pressure-volume data. The tension-area relationship so derived is similar to that of bubbles of nasal mucus, but depends upon an assumed