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Research Article

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Serial measurements of C_A indicated a progressive increase beginning at about 6 months of gestation and a return to normal by 2 months postpartum.

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Pulmonary Mechanics during Pregnancy *

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Summary. Previously reported changes in static lung volumes during pregnancy have been confirmed.

Measurements of lung compliance (C_L) and total pulmonary resistance (R_L) were made in 10 women in the last trimester of pregnancy and 2 months postpartum, employing an esophageal balloon and recording spirometer. C_L was unaffected by pregnancy, but R_L was 50% below normal during pregnancy.

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Introduction

The mechanical properties of the lungs in pregnant women are of interest for several reasons. First, there is a conflict between the complaints of dyspnea made by many women during pregnancy and the remarkably benign clinical course shown by women with pulmonary resections during pregnancy (1). Secondly, detailed spirometric studies, notably by Cugell, Frank, Gaensler, and Badger (2), have indicated a progressive reduction in the functional residual capacity (FRC) and expiratory reserve volume (ERV) as term approaches. The reduction in the resting lung volume might be expected to be associated with an increase in airway resistance (R_A), which is known to be volume dependent (3). This reduction in FRC is in contrast with the preservation of the vital capacity (VC). The preservation

of VC suggests that lung compliance (C_L) is not greatly changed. Third, metabolic changes occurring in pregnant women might modify pulmonary mechanics. Hypocapnia occurs during pregnancy (4), and this is known to increase airway resistance (5). However, hormone-determined changes in smooth muscle tone and possibly connective tissue elastance might occur during pregnancy and so could possibly alter the mechanical properties of the respiratory system.

Although there are extensive observations of many aspects of respiration during pregnancy (6), there are no published studies of the effects of pregnancy on lung compliance (C_L) and only one report (7) indicating a reduction in total pulmonary resistance (R_L) demonstrated by the interruptor method.

Methods

Lung volumes were determined on a 9-L Collins spirometer. FRC was measured by the helium dilution method.

Pulmonary mechanics. Lung compliance was measured by the method of Neergard and Wirz (8) employing a model 370 wedge spirometer (Med-Science Electronics) to monitor volume and flow. The wedge spirometer provides electrical calibrations for volume and flow. These were periodically checked with a Collins 9-L spirometer

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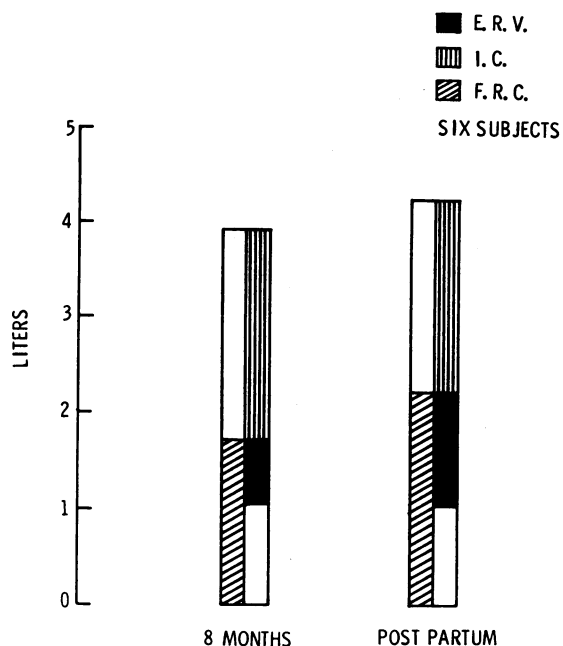


FIG. 1. A COMPARISON OF THE STATIC LUNG VOLUMES AT THE EIGHTH MONTH OF PREGNANCY AND POSTPARTUM. ERV = expiratory reserve volume; IC = inspiratory capacity; FRC = functional residual capacity.

for volume and a Rotameter flowmeter to provide constant flows of up to 6 L per second, whose values were predetermined volumetrically. Transpulmonary pressure was obtained by using an esophageal latex rubber balloon, 10 cm in length and 3 cm in circumference, a PE 160 catheter, and Sanborn 270 pressure transducer. Recordings were made on an Electronics for Medicine recorder. The balloon was positioned to obtain the highest negative end expiratory pressure and contained 1 ml of air. Measurements of C_L were obtained during breathing by comparing pressure and volume changes at points of zero flow. C_L was studied during normal quiet breathing at FRC.

Total lung resistance was calculated by the isovolume method, which relates changes in pressure to changes in flow at constant volume (8).

Airway resistance was measured in a constant pressure body plethysmograph, designed by Mead (9). Volume was measured by a Krogh spirometer and Linearsyn transducer. Flow was measured by a heated wire mesh screen pneumotachograph and Statham PL-5 pressure transducer. A linear response was obtained up to flow rates of 2.5 L per second. Mouth pressure was obtained from a Sanborn 270 pressure transducer. Flow and volume or pressure and volume were observed on the x-y screen of an Electronics for Medicine recorder. The resistance of the circuit was 0.2 cm H_2O per L per second. The procedures for measuring R_A are as follows: The subject was comfortably seated in the plethysmograph while temperature stabilization occurred. Panting res-

pirations at flow rates of about 1.0 L per second were begun to obtain flow/volume slopes on the x-y recorder. An airway interruptor was then closed while panting continued against the shutter to obtain pressure/volume slopes. R_A and total gas volume (assumed to be intrathoracic) were calculated by the method of DuBois (3), from the ratio of the two slopes and the appropriate calibration factors. Six measurements were obtained at the subject's resting lung volume. Additional measurements of R_A were obtained at progressively larger volumes, and finally at volumes below the resting lung volumes.

Subjects were nursing and secretarial staff, aged 20 to 25 years, who had no history of pulmonary disease and were free from upper respiratory infections at the time of testing. No attempt was made to match pregnant and nonpregnant women for body size. All but one of the pregnant women were primigravida.

Types of studies. Four types of comparison were made. (The willingness of some pregnant women to perform all the studies proved limited, and, therefore, the comparative groups are somewhat variable.) 1) Lung volume measurements only were made in 6 separate subjects. 2) Lung compliance and total pulmonary resistance were studied in 10 subjects during pregnancy and after delivery. 3) Airway resistance was compared in 14 control and 13 pregnant women. Five of these pregnant subjects were also studied by comparison 2; the other 8 were unwilling to swallow the balloon. 4) The serial changes in airway resistance during pregnancy were followed in 6 subjects. In 5 of these, comparisons 2 and 3 were also completed. In the other 1, only data for the serial studies were obtained. Where only 1 technique was employed, the procedure outlined for each method was followed. Where both balloon and plethysmography were used, the esophageal pressure method was employed first.

Results

Lung volumes. In a separate pilot study, static lung volumes alone were measured in 6 subjects who were about 8 months pregnant and then 2 months postpartum. The data are indicated in Figure 1, where the average of the 6 subjects is indicated. During late pregnancy, there is a 25% reduction in FRC and about 40% reduction in ERV. Slight and statistically insignificant reductions in total lung capacity and VC were also found. VC is maintained by the increase in inspiratory capacity. The changes were consistent in all subjects. These data agree with the more extensive studies of Cugell and his associates (2) in 19 subjects.

Airway resistance. In clinical practice the term R_A is more commonly used than its reciprocal, C_A . However, C_A bears a near linear relationship to

the lung volume (3). The use of C_A has two advantages. First, comparisons of the relationship between C_A and the resting lung volumes without reference to the subject's body size may be made. This is accomplished by expressing the data as C_A/L of lung volume, the so-called specific airway conductance. Anthropometric factors determine C_A by their relation to lung volumes (e.g., FRC). The use of specific C_A therefore permits an estimate of airway conductance adjusted for body size. Second, direct comparisons may be made of the rate of rise in C_A as the lung is voluntarily inflated.

The first comparison of C_A between pregnant and nonpregnant women is shown in Figure 2, which indicates the specific airway conductance in 2 groups, namely, 14 control women and 13 pregnant women of similar age. The values in the pregnant women were obtained at a mean of $7\frac{1}{2}$ months of gestation. When pregnant subjects were studied serially, the data obtained nearest to term were employed. These values for specific C_A were obtained from C_A and volume data observed at resting lung volumes. The use of such data obtained near FRC is important to minimize the between-groups variations in the regression slope relating C_A to lung volume. The data indicate that, although there are considerable within-group variations, the mean specific C_A of pregnant

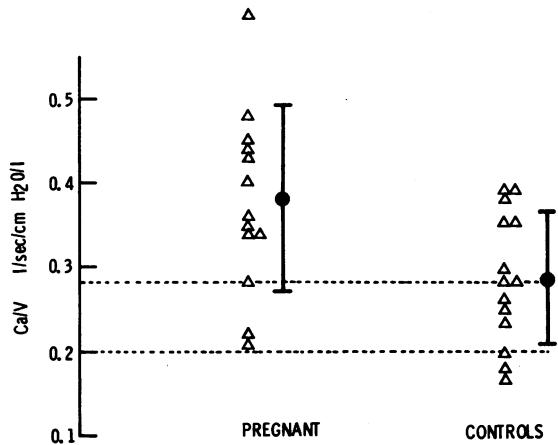


FIG. 2. A COMPARISON OF SPECIFIC AIRWAY CONDUCTANCE (C_A) IN PREGNANT AND NONPREGNANT WOMEN. V = lung volume. Broken lines indicate the normal range.

women is 36% higher than the mean specific C_A of nonpregnant women ($p < 0.05$). The mean specific C_A in the control group is within the normal range of 0.20 to 0.28 reported by DuBois (3).

An evaluation of the differences in the regression relation between C_A and lung inflation in these two groups is shown in Figure 3. Only those subjects in both groups whose lung volume during airway resistance studies exceeded 1.5 L have been employed, yielding data on 9 control and 8 preg-

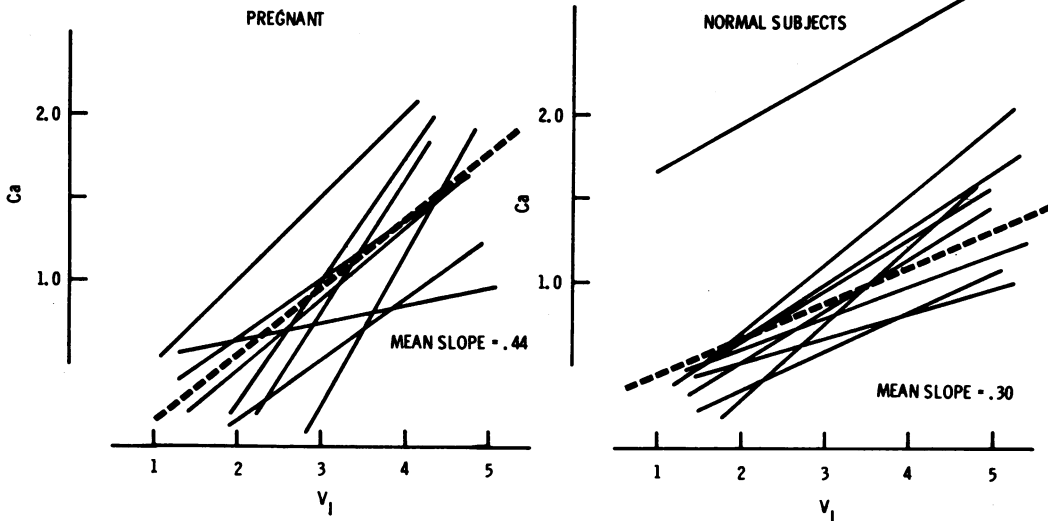


FIG. 3. A COMPARISON BETWEEN THE REGRESSION LINES RELATING C_A TO V_L IN PREGNANT AND NONPREGNANT WOMEN. Solid lines represent the regression lines for each subject. Broken lines represent the mean of the slopes in each group.

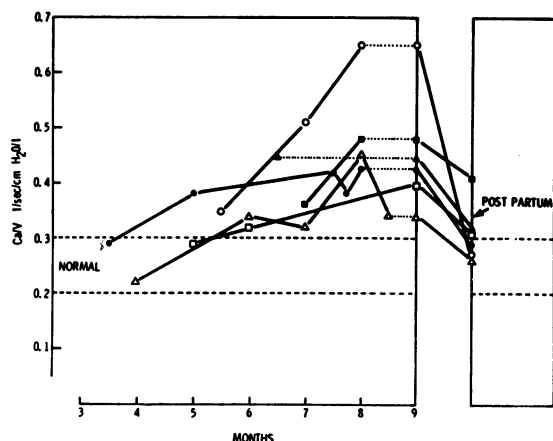


FIG. 4. TIME COURSE OF SPECIFIC C_A DURING PREGNANCY IN 5 SUBJECTS. Dotted lines are constructional and join the last observation during pregnancy to the 9-month vertical to permit comparison with the postpartum data.

nant women. This lung volume range requirement was necessary to permit the calculation by the method of least squares of the regression coefficient between C_A and lung volume for each subject. The Figure indicates the calculated regression lines. The data found in control subjects showed a mean slope of 0.30 ± 0.10 , which compares with the normal range reported by DuBois of 0.13 to 0.35 (3). The mean slope of the pregnant women was 0.44 ± 0.28 . These slopes were compared by the Student t test and were significantly different ($p < 0.01$). Thus, during pregnancy, there is an unusually large increase in C_A as the lung is progressively inflated.

Time course of the change in airway conductance. In 6 pregnant women, serial observations of the specific airway conductance were made. These data are shown in Figure 4, which indicates the specific C_A during pregnancy and postpartum (4 to 6 weeks after delivery). There is a rise in specific C_A , particularly in the third trimester of pregnancy, with a striking return to normal by about 5 weeks after delivery. The exact time course of specific C_A after delivery is not known, since it was not practical to obtain studies in the immediate postpartum period.

Lung compliance and total pulmonary resistance. The measurement of C_L and R_L by the esophageal balloon technique depends on the assumption that during breathing, the changes in intrapleural and

esophageal pressures are equal. The direct comparison is clearly impossible in pregnant normal subjects, but some information may be obtained from a consideration of end expiratory pressures (EEP) during tidal breathing at FRC. Table I includes a comparison in 10 women between the values of EEP in the third trimester of pregnancy and about 5 weeks postpartum. The postpartum values are, in general, negative with a mean of -2.7 cm H_2O . These are within the reported normal ranges. However, during pregnancy a striking difference is observed. The EEP as measured in the balloon is positive, with a mean of $+1.7$ cm H_2O . This positive esophageal pressure cannot equal true transpulmonary pressure at a moment where there is no gas flow. Thus, the assumption that changes in esophageal pressure still reflect changes in transpulmonary pressure is required, if estimates of C_L are to be derived. A somewhat similar assumption is, of course, needed for the calculation of R_L by the isovolume method. The estimates of C_L and R_L are indicated in Table I and were derived on the basis of these assumptions. To the extent that such calculations are valid (see Discussion), our data indicate that, although C_L does not change, there is a highly significant change in R_L ($p < 0.01$). The mean R_L during pregnancy is half that observed postpartum.

TABLE I

A comparison of end expiratory pressures (EEP), lung compliance (C_L), and total pulmonary resistance (R_L) in 10 subjects during pregnancy and postpartum

Subject no.	Pregnant			Postpartum			
	EEP	C_L	R_L	EEP	C_L	R_L	Predicted C_L †
	cm H_2O	L/cm H_2O	cm H_2O /L/sec	cm H_2O	L/cm H_2O	cm H_2O /L/sec	L/cm H_2O
1	4.2	0.13	0.2	-3.1	0.13	2.3	0.14
2	2.7	0.11	1.5	-4.4	0.11	0.8	0.12
3	1.2	0.12	1.2	-8.6	0.14	1.9	0.17
4	3.1	0.16	0.5	-3.0	0.19	2.1	0.13
5	1.5	0.09	0.7	-2.5	0.13	1.7	0.14
6*	2.2	0.14	0.9	-0.6	0.11	2.0	0.15
7*	-0.8	0.23	1.1	-1.5	0.22	1.8	0.15
8*	2.2	0.13	0.8	+1.2	0.13	3.2	0.15
9*	-0.1	0.21	0.5	-3.2	0.20	1.0	0.18
10*	0.9	0.09	1.2	-1.2	0.20	1.5	0.16
Mean	1.7	0.14	0.9	-2.7	0.16	1.8	0.15
SD		0.047	0.39		0.042	0.47	

* Subjects shown in serial studies in Results under "airway resistance."

† Predicted $C_L = (0.00343 \times \text{height in centimeters}) - 0.425$ (10).

Discussion

Esophageal pressure during pregnancy

Before indicating the significance and possible mechanisms of these findings, we should discuss the validity of the esophageal balloon pressure changes as measures of changes in transpulmonary pressures during pregnancy. The following technical considerations apply: 1) Every effort was made to position the balloon in the midesophagus; 2) cardiac impulses were clearly visible in the records; these impulses show the usual amplitude of about 0.5 cm H₂O; 3) the balloon was not over distended, since only 1 ml of air was introduced into the balloon; 4) in two subjects (No. 6 and 7) in whom serial studies were performed during pregnancy, progressive rises in EEP occurred from -4.5 and -2.5 at 28 weeks to values at 36 weeks of -0.1 and -0.8 cm H₂O; 5) no excessive esophageal contractions were evident in the records; 6) the normal range of EEP in the postpartum women argues that balloon positioning was correctly performed in the postpartum state. Thus, it appears that a positive EEP during pregnancy is not due to the use of an improper technique, but reflects a genuine disparity between the esophageal and intrapleural pressures during late pregnancy.

As discussed earlier, positive transpulmonary pressures cannot occur at end normal expiration, and, therefore, the measured esophageal EEP values cannot reflect the absolute transpulmonary pressures. This raises the problem as to the effect of these EEP values on calculated C_L and R_L. We cannot directly compare intrapleural and esophageal pressures in pregnant women, but there is a highly relevant analogy between pregnancy and the supine posture. The analogy includes a positive resting EEP (11-13) in normal supine subjects, and, further, the supine posture is associated with an ascent of the diaphragm. An alteration from sitting to supine posture produces changes in lung volume profile similar to those encountered in pregnancy, including lowered FRC, increased IC, and a normal VC. More recently, Chiang and Lyons (14) studied the effects of a 45° tilt towards the supine position. They showed that esophageal EEP changes from -3.74 to -2.71 cm H₂O and that FRC falls by 200 ml as a result of this tilt. The full 90° tilt towards a

supine posture was studied by Mead and Gaensler (12), who compared intrapleural and esophageal pressures. They showed that lying supine causes the directly measured end expiratory intrapleural pressure to change from -5.1 to -1.1 cm H₂O, while the end expiratory balloon pressure changes from -4.8 to +2.7 cm H₂O. Thus, the supine posture is associated with a lack of agreement between pleural and balloon static pressure differences. These authors concluded that "measurements of compliance in the tidal range would be factitiously low as measured from esophageal pressure in the supine position" (12). This point was further developed by Knowles, Hong, and Rahn (13) and separately by Ferris, Mead, and Frank (15), who showed differences in the static pressure-volume diagram in 2 postures when the esophageal balloon was employed for the measurement of transpulmonary pressure. Both groups indicate that the greatest differences exist in the lower half of lung volume, and agree that the apparent supine C_L calculated from balloon pressures at small tidal volumes would appear to be about 25% less than sitting values. The range of the percentage change in C_L between the two postures is 0 to 40% (15).

Our data indicate a normal postpartum C_L evidenced by comparing the C_L observed and that predicted from the subject's height (Table I). The apparent C_L during late pregnancy is not statistically different, but the mean value is lower by 0.02 U, that is, 12% lower than postpartum. This change is of similar magnitude to the apparent change reported for the supine studies. Thus, if the analogy between pregnancy and the supine posture is valid, it may be concluded there is no change in C_L. This conclusion is supported by the preservation of the VC during pregnancy.

The isovolume method for the calculation of R_L requires less discussion. The method does assume 1) that the elastic component of pleural pressure is constant for any lung volume, irrespective of the phase of respiration (i.e., no significant hysteresis); 2) that any differences between pleural and esophageal pressures are constant at a given lung volume; and 3) that the time constants of the lung are sufficiently rapid for pressure equalization. There are no reasons to question the applicability of assumptions 1 and 2 to pregnant women during quiet tidal breathing. The time

constant derives from the product of R_L and C_L . C_L has been shown to be normal, and R_A , the larger component of R_L , is, in fact, decreased. The time constant of the lungs of pregnant women is, therefore, sufficiently rapid to validate assumption 3.

Airway and total pulmonary resistance

Total pulmonary resistance (R_L) is known to include 2 components. The larger component is airway resistance (R_A), and the smaller one derives from tissue resistance. Thus, a comparison of R_L to R_A is pertinent. Two such comparisons are presented in Table II. Section A compares the two methods on all subjects who were studied by each method. This comparison is, at best, a general one since these mean data are derived from studies of R_A and R_L in groups that included different subjects. Section B presents a better comparison since these data were obtained on the same subjects. This comparison indicates that approximately 80% of the reduction in R_L during pregnancy derives from the reduction in R_A . It is not possible to state whether the tissue-resistive component is altered during pregnancy since this component is too small for precise measurement. A third comparison between R_L and R_A is achieved by correlating the two measures on the same subjects. This may be shown by comparing the reciprocal of R_A , namely C_A , and $1/R_L$. Figure 5 presents this comparison. The two methods correlate fairly well ($r = 0.61, p < 0.025$), and the regression coefficient of C_A on $1/R_L$ is 0.77, a value not significantly different from 1.0. C_A in general exceeds $1/R_L$ as would be required by the presence of an additional tissue-resistive component in R_L . This comparison again can only be approximate,

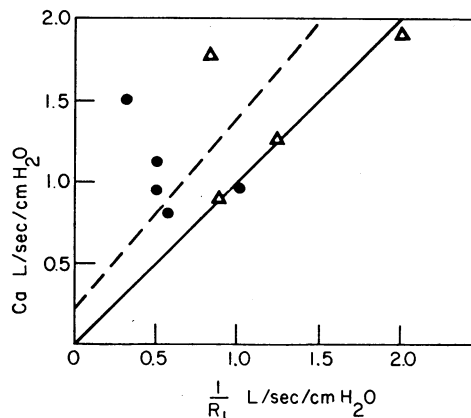


FIG. 5. COMPARISON BETWEEN C_A AND $1/R_L$ (TOTAL PULMONARY RESISTANCE) FOR THE SAME SUBJECTS. Δ = pregnant; \bullet = postpartum. Solid line is the line of identity. Broken line is the calculated regression line of C_A on $1/R_L$.

since the flow rates and the lung volumes were only approximately similar during the applications of the 2 methods.

Mechanism of changes in airway conductance

The rise in C_A at a constant flow during pregnancy clearly indicates an increase in airway cross-sectional area. The effects of pregnancy on certain factors known to modify airway size may now be considered.

Lung volume and elastic recoil. It has been demonstrated by Caro, Butler, and DuBois (16) that temporary restriction of thoracic or abdominal mobility by external straps results in an increase in specific C_A . This increase in specific C_A was shown to depend on a diminished C_L . The analogy between external strapping of the abdomen with possible restriction of the diaphragm and restriction by the enlarging uterus suggests a common mechanism for an increased specific C_A . However, our data do not indicate any change in C_L during pregnancy. Further, in spite of a higher end normal expiration position of the diaphragm, there can be no true restriction of diaphragm movement since the VC is preserved during pregnancy.

Effects of lung inflation. The volume history of the lung before the measurement of its mechanical properties has been shown to influence both C_L and R_A . Since the lung during pregnancy has a reduced resting volume, this effect might be

TABLE II

A comparison of total pulmonary resistance (R_L) and airway resistance (R_A)*

		No. of subjects	cm H ₂ O/L/sec	
			Pregnant	Postpartum
A	R_L	10	0.9	1.8
	R_A	13	0.9	1.1
B	R_L	5	0.9	1.9
	R_A	5	0.7	1.5

* Group A = unmatched subjects; group B = matched subjects. (For explanation see text.)

potentiated. However, the sequence of our studies, and particularly the change in R_L shown after a rest period in the laboratory, do not support this explanation.

Metabolic factors. One important metabolic change during pregnancy is the increased levels of various hormones. These might reduce airway resistance. Three possible hormones might be considered. Progesterone levels rise progressively during pregnancy, and the decreased tone in certain smooth muscles, namely in the ureters, has been attributed to progesterone (17). This effect also occurs at the sixth to seventh month of pregnancy. Thus, progesterone might reduce normal bronchomotor tone.

The production of cortisone and related steroids is also well known to be increased during pregnancy. One may speculate that these steroids also modify normal bronchomotor tone.

Relaxin is known to mobilize cartilaginous structures in pregnant lower mammals (18), and it is conceivable that similar effects occur in pregnant women. However, too little is known about relaxin to permit further discussion of this point.

The possible relationship between hormonal changes during pregnancy and decreased R_A is intriguing but speculative.

Dyspnea and work of breathing during pregnancy

Bader, Bader, and Rose (19) demonstrated a progressive increase in the O_2 cost of breathing under standardized patterns of respiration during the last 4 months of pregnancy. These authors suggested that these increased O_2 costs of breathing were not related to altered lung mechanics, but rather to increased diaphragmatic work. Our data indicating an unchanged C_L and reduction in both R_L and R_A support their view.

The demonstrated reduction in R_A during pregnancy cannot account for the "dyspnea of pregnancy." The reduced R_A is, however, probably relevant to the failure of pregnancy to cause respiratory embarrassment in patients with lung resections. Gaensler, Patton, Verstraeten, and Badger (1) studied 7 such patients in whom the vital capacities were reduced to a mean of 1.4 L. The alterations in the static lung volumes during pregnancy were similar to those of normal women. It is reasonable, therefore, to presume that R_A

was reduced in such patients. Gaensler and associates specifically indicate that these patients did not complain of dyspnea during pregnancy. In these patients, the increased ventilatory demands of pregnancy must be met by rises in the respiratory rate. Thus, a reduced R_A assumes some importance in minimizing the increase in total respiratory work and might possibly relate to the absence of dyspnea.

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