Mechanics of Breathing During Anesthesia.
2. The Influence of Airway Adequacy

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Pulmonary compliance (C_L) and resistance (R_L) were measured simultaneously in 13 supine patients prior to operation in both awake and anesthetized states. During anesthesia three airway situations were compared: (1) mask, no airway, (2) mask, oral airway, and (3) endotracheal airway. During mask anesthesia R_L was 123 per cent above the control without oral airway, 55 per cent above the control with oral airway, and with tracheal intubation R_L decreased to 18 per cent below the control. During periods of increased R_L with mask, such "subtle" obstruction was clinically undetectable, not accompanied by decreased tidal exchange. The primary reason for elevated R_L during mask anesthesia was due to increases in upper airway resistances. Compliance fell approximately 15 per cent during anesthesia, remained at a depressed level and was uninfluenced by the type of airway or its adequacy.

NORMAL pulmonary mechanics may become abnormal in the spontaneously breathing anesthetized patient as evidenced by decreased compliance and increased resistance.[1-5] In the spontaneously breathing patient, hypoxemia has been demonstrated. The reason proposed is gradual atelectasis with venous-arterial shunting.[5-10] Increased work of breathing, subsequent overproduction of carbon dioxide and demand for more oxygen contribute further to deviation from the normal.[4, 5] However, little is known about simultaneous behavior of the two components of pulmonary mechanics, pulmonary compliance (C_L) and resistance (R_L). In addition, little is known about the influence of the airway on mechanics during anesthesia.

An obstructed airway offers increased resistance to breathing. In this instance, how does compliance change and how important is the degree of airway obstruction? Complete obstruction, such as from laryngospasm, results in neither tidal exchange nor gas flow. Partial obstruction results in decreased tidal exchange, decreased gas flow rates, and increased changes in both airway and transpulmonary pressures. Do lesser degrees of obstruction exist in which an adequate tidal exchange is present? We believe that they do and it is the purpose of this investigation to relate the type of airway and its adequacy to simultaneous compliance and resistance during general anesthesia in supine, spontaneously breathing man. We propose that these lesser degrees of obstruction be called "subtle obstruction" since they are clinically undetected and yet may significantly increase work of breathing in spontaneously breathing patients.

Experimental Method

The technique of measuring transpulmonary pressure (P_T), flow rate ($\dot{V}$), and tidal volume (V_T) continuously via a pneumotachograph and integrator in the supine, anesthetized patient has been described.[11] Instrumentation included appropriate transducers, a carrier-amplifier, oscilloscope, and rapid-writing attachment. C_L and R_L were calculated from a series of breaths (average 25) from which changes in P_T, $\dot{V}$, and V_T were obtained. Figure 1 demonstrates the method of calculating expiratory compliance and isovolume resistance. In this present study such measurements were made prior to operation in the conscious state and during the spontaneously breathing anesthetized state when the type of airway was varied.

Thirteen patients were premedicated with 100 mg. of pentobarbital and 0.4 mg. of scopolamine intramuscularly approximately 1 hour prior to entering the anesthesia labora-

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TABLE 1. Pulmonary Compliance (C_L) and Resistance (R_L) as Influenced by Type of Airway During Anesthesia

Patient	Sex	Age	Height (inches)	Weight (lbs.)	Primary Anesthetic Agent	Thiopental (mg.)	Awake Control		Anesthetized					
							C_L cm. H_2O	R_L cm. H_2O/l./sec.	No Airway		Airway		Endotracheal	
									C_L	R_L	C_L	R_L	C_L	R_L
1	F	35	65	186	Halothane	250	0.07	5.7	0.14	13.2	0.05	7.4	0.06	4.6
2	M	29	70	168	Halothane	350	0.06	6.9	0.12	38.2	0.07	15.3	0.09	6.1
3	M	57	71	156	Halothane	250	0.15	5.4	0.13	8.6	0.14	8.5	0.09	4.8
4	F	33	64	182	Halothane	—	0.11	2.2	0.09	5.0	0.07	8.6	0.12	1.7
5	F	38	64	143	Halothane	50	0.05	9.6	0.05	22.3	0.06	24.3	0.02	15.9
6	F	35	62	137	Halothane	250	0.14	15.9	0.10	20.2	0.06	19.8	0.05	9.5
7	M	25	72	141	Halothane	—	0.15	6.2	0.07	18.4	0.14	4.7	0.26	3.0
8	M	22	68	145	Methoxyflurane	175	0.12	8.2	0.06	30.0	0.09	21.3	0.09	7.5
9	F	40	66	133	Halothane	—	0.04	10.2	0.07	8.6	0.05	10.2	0.04	9.1
10	F	44	62	128	Halothane	100	0.05	6.8	0.05	12.8	0.07	6.9	0.06	5.6
11	F	28	63	112	Methoyxflurane	150	0.12	4.1	0.12	9.1	0.13	4.3	0.13	2.3
12	M	58	69	159	Halothane	250	0.33	12.7	0.17	27.0	0.23	3.6	0.14	4.0
13	F	34	66	141	Methoxyflurane	375	0.14	5.9	0.09	10.7	0.14	17.3	0.11	7.7
Range		22–58	62–72	112–186		50–375	0.04–0.33	2.2–15.9	0.05–0.17	2.7–38.2	0.05–0.23	3.6–24.3	0.02–0.26	1.7–15.9
Mean		37	66	148		220	0.12	7.7	0.10	17.2	0.10	11.7	0.10	6.3

tory. Ten had thiopental inductions; 10 were given halothane, and 3 methoxyflurane as the primary anesthetic. Fifty per cent nitrous oxide in oxygen was used with the primary agent. Succinylcholine chloride, 60–80 mg. was employed for tracheal intubation and no other agents used.

Results

Table 1 lists pertinent descriptive data and the changes in C_L and R_L as influenced by type of airway in 13 patients. Four airway situations were compared: (1) awake, mask, control; (2) anesthetized, mask, no oral airway; (3) anesthetized, mask, oral airway; and (4) anesthetized, endotracheal airway.

During the second situation (anesthetized, mask, no airway), R_L more than doubled while the C_L decreased approximately 20 per cent (fig. 2). During the third situation (anesthetized, mask, oral airway), R_L remained elevated at approximately 50 per cent above the control but decreased upon insertion of oral airway; C_L remained at the previously depressed level. During the fourth situation (endotracheal airway), R_L fell to below the control level while the C_L remained at the previously depressed level.

An example of how the R_L and C_L changed during general anesthesia is demonstrated in figure 3. Corresponding changes in pressures, flows, and tidal volumes have been arranged in chronologic order. This patient had normal measurements for awake R_L and C_L. Anesthesia was induced with halothane-nitrous oxide-oxygen; and during 20 minutes of mask anesthesia, this patient developed an R_L ranging from two to three times that of the control value. With insertion of the oral airway and, subsequently, tracheal intubation, R_L fell to and remained below the control level. C_L fell during anesthesia although it increased when both oral airway and endotracheal tube were inserted, with a single decrease at 26 minutes. C_L also increased to above the control at about 40 minutes of anesthesia at which time R_L was at its lowest. The relationship between changes in V_T and C_L should be noted.

Discussion

The absolute C_L and R_L figures found in this study are low and high, respectively, when compared with data from conscious subjects in the sitting position. It has been accepted that esophageal pressure swings in the supine position are reasonably accurate although absolute pressure may be inaccurate. *Changes* in C_L and R_L (including deviations from the control) are believed to be quite real. There are two possible reasons for these apparent deviations in C_L and R_L from accepted norms: (1) high absolute esophageal pressures in the supine position produced by the weight of the heart on the intraesophageal balloon[12]; (2) endotracheal tube resistances (at a 40 liters/minute flow, approximately 1 cm. of water/liter/second) were not subtracted. The absolute figures when compared with C_L and R_L measurements in the literature in supine, anesthetized humans show a striking similarity.[1-5] Because of this and because *changes* in C_L and R_L, as influenced by the airway, were sought we believe the great deviations from the control figures are particularly significant.

The significant findings in the present investigation center about the influence of the endotracheal tube and changes in R_L. During mask anesthesia 12 of 13 patients without oral airway and 10 of 13 with oral airway demonstrated increased R_L although such increases were not clinically diagnosed. Tidal exchanges during this period of obstruction (which we have termed "subtle") remained adequate although decreased (fig. 2). Only when the endotracheal tube was inserted did the increased R_L fall to the awake, control level in all 13 patients. This increase in R_L involved upper airway resistance primarily because it was reduced significantly with insertion of the endotracheal tube. This is because the elevated R_L during mask, no airway anesthesia and oral airway anesthesia was reduced to 18 per cent below the control level with tracheal intubation. Recent investigations indicate that total airway resistance in awake, sitting subjects at functional residual capacity may be divided into upper and lower components, both of which contribute approximately 50 per cent to the total.[13, 14] Wu, Miller and Luhn[5] had patients whose R_L was lower after tracheal intubation than during the awake, control.

There are many possible causes of obstructed airway in the supine patient anesthetized with mask. Fink has suggested three mechanisms referable to the upper airway including reflex and passive closure of both larynx and glottis.[15] Alinearity of the flow-pressure relationships in the human lung in the mid-range of lung volume has been demonstrated to result primarily from upper airway resistance.[16] It seems reasonable to conjecture that upper airway resistance contributed sig-

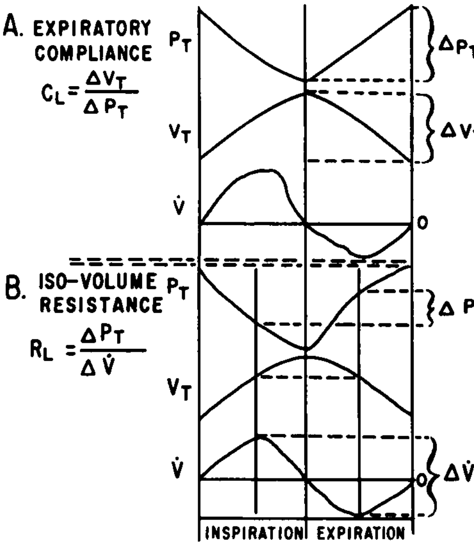

FIG. 1. Modified from Amdur, M. O. and Mead, J.: Mechanics of respiration in unanesthetized guinea pigs, Amer. J. Physiol. 192: 364, 1958.

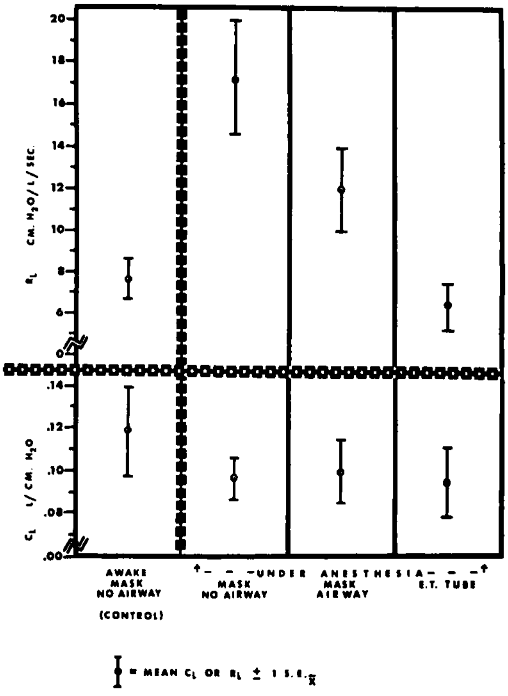

FIG. 2. Changes in pulmonary compliance (C_L) and resistance (R_L) in 13 patients as influenced by type of airway and anesthesia.

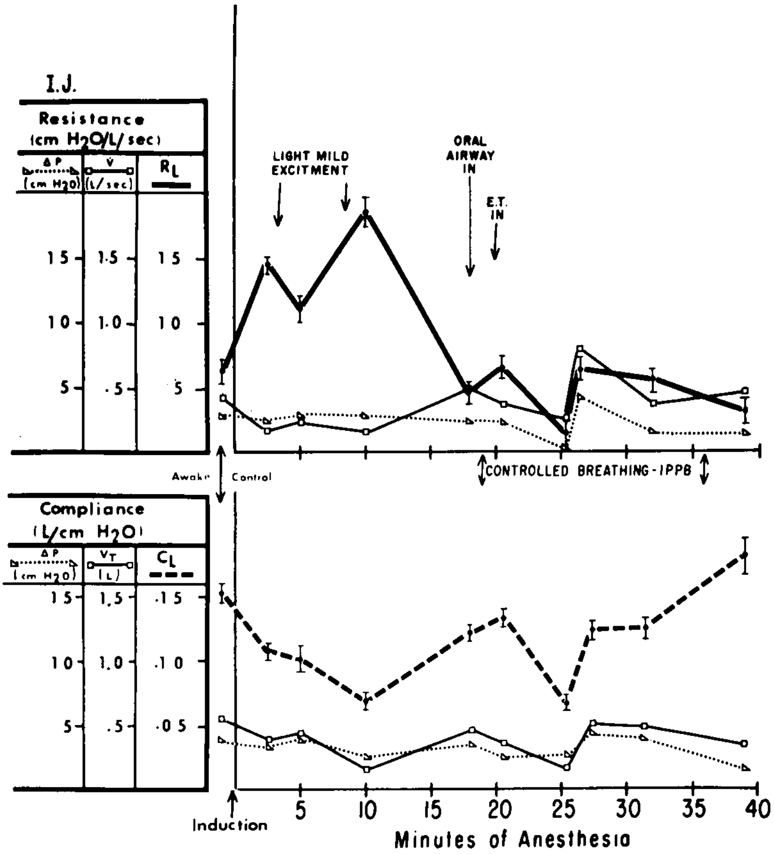

FIG. 3. Simultaneous pulmonary compliance (C_L) and resistance (R_L) with corresponding pressure, volume, and flow changes during halothane anesthesia.

nificantly to the total resistance elevation during mask anesthesia so that prolonged periods of such "subtle airway obstruction" during anesthesia would prove harmful.

The C_L changes during anesthesia as reported were less labile and dramatic than R_L changes and quite independent of the influence of airway or its adequacy. In general C_L remained depressed regardless of airway at about 20 per cent below the control level. Decreased C_L during anesthesia has been related to relative hypoxemia during both spontaneous[5] and constant volume intermittent positive-pressure breathing.[17] The cause of this aberration is unknown but the premise that atelectasis occurs has been suggested. The reduction in ventilation-perfusion ratio that follows causes a relative venous to arterial shunt leading to lowered arterial P_{O_2}.[5,10] Another factor whose role is as yet unclear is surface tension.[18] Higher pressures are necessary to inflate collapsed alveoli than to keep open alveoli uncollapsed[6]; this may be related to surface tension phenomena.

The relationship between decreased V_T and decreased C_L during anesthesia has been demonstrated.[11] It has never been conclusively shown but there is reason to believe that in supine, anesthetized man FRC decreases. Lowered FRC has been correlated with a decrease in C_L during both deep and shallow breathing in conscious man.[18] Compliance has been demonstrated to decrease significantly in conscious, sitting volunteers whose FRC was decreased by chest strapping to one liter below the control level.[19] These subjects also demonstrated increased R_L and evidence of shunting.

Observation of changes in C_L and R_L in chronologic fashion demonstrated that while some patients exhibited a positive relationship between changes in simultaneous C_L and R_L, others had negative correlations. In general, changes in C_L and R_L have been accepted as being unrelated unless extreme increases in R_L occur as during true bronchospasm or extremely rapid rates of breathing.[20]

Summary and Conclusions

Pulmonary resistance and compliance measurements were made simultaneously in 13 supine patients during an awake, control period and again during anesthesia as varied with mask-no airway, mask-oral airway, and endotracheal airway. Resistance (R_L) proved to be more labile than compliance (C_L). R_L was 123 per cent above the control value during mask, no airway anesthesia. These patients' airways were usually not overtly obstructed. Rather, this obstruction was clinically undetected and not accompanied by decreased tidal exchange. With insertion of the oral airway this elevated R_L was lowered, but only to a level 55 per cent above the control value.

In all patients, with insertion of the endotracheal tube, R_L fell to a mean figure of 18 per cent below the control level. It is concluded that the endotracheal tube decreased the elevated upper airway resistance (as contrasted to lower airway resistance) during mask anesthesia.

Compliance fell approximately 15 per cent during anesthesia and was uninfluenced by the type of airway or its adequacy.

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