Measurement of Airway Resistance in Anesthetized and Paralyzed Subjects: Proposal for Evaluation of K_1 Values

Takayuki SAKAI, Hitoshi YOSHIDA, Hirofumi YANO
and Masuhiko TAKAORI

The effects of lung volume and respiratory airflow on airway resistance were studied in five anesthetized and paralyzed patients. Airway resistance measured during the inspiratory phase with intermittent constant airflow inflations decreased in inverse correlationship to increases in lung volume. Airway resistance measured during the expiratory phase with an airway interruption technique, on the other hand, increased with a linear relationship to the expiratory airflow as expressed by a function of $Y=K_1 + K_2X$. K_1, calculated from the values of airway resistance corresponding to three different airflows, was unaffected by intentional expiratory resistance loading. Thus, simultaneously with the measurement of airway resistance by this method, expiratory gas sampling with a Douglas bag can be done if necessary. Since the K_2 value of the endotracheal tube used in this study (Portex® I.D. 8 mm, length 26 cm) was quite high ($5.0\ cmH_2O \cdot l^{-2} \cdot sec^2$), depending on the airflow, the presence of the endotracheal tube strongly affected the measurement of airway resistance during general anesthesia. K_1 measured by the above method, however, may be considered as the best way to evaluate the lower airway resistance independent of either lung volume or expiratory airflow.

(Key words: airway resistance, measurement, general anesthesia, airflow, lung volume)

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Between 1979 and 1985 we carried out three studies to investigate the effects of inhalational anesthetics, beta blockades and calcium antagonists on airway dynamics during general anesthesia using an oscillation method[1], a constnat flow inflation method[2] and an airway interruption method[3], respectively. We were unable, however, to determine which method was the most accurate for measuring airway resistance during general anesthesia.

In this study, airway resistance was measured by constant flow inflations and interruptions of expiratory flow in five patients anesthetized with NLA anesthesia and ventilated mechanically with a muscle relaxant. The effects of lung volume, respiratory airflow and intentional loading of expiratory resistance on airway resistance were studied and an attempt was made to obtain the most universal expression of airway resistance under controlled ventilation in anesthetized and paralysed patients.

Materials and Methods

Five patients (one female and four males),

Department of Anesthesiology, Kawasaki Medical School, Kurashiki City, Okayama, Japan

Address reprint requests to Dr. Takayuki Sakai: Department of Anesthesiology, Kawasaki Medical School, 577 Matsushima, Kurashiki City, Okayama, Japan 701-01

Table 1. Physical characteristics and values of preoperative standard pulmonary funciton tests in five subjects

Subj. No.	Sex	Age, yr	Body Wt., kg	Height, cm	%VC	$FEV_1/VC\%$
1	M	60	57	155	115	74
2	M	60	66	163	88	76
3	F	35	69	164	116	82
4	M	53	62	162	107	83
5	M	55	50	164	100	82
Mean ± SD		52.6 ± 10.3	60.8 ±7.5	161.6 ± 3.8	105 ± 11	79 ± 4

who had been proposed for surgery under general anesthesia in the central operating room of Kawasaki Medical School Hospital and who had no particular abnormalities in their respiratory or cardiovascular systems preoperatively, were the subjects of this study. The physical characteristics and values of preoperative standard pulmonary function tests are shown in table 1. The mean age of the patients was 53 ± 10 years, their mean weight was 61 ± 8 kg, and their mean height was 162 ± 4 cm.

At 30 min prior to the inductin of anesthesia, 0.5 mg of atropine sulfate, 15 mg of pentazocine and 50 mg of hydroxyzine pamoate were injected subcutaneously. After preoxygenation, the patients were anesthetized by intravenous administration of 200 mg of thiopental sodium and were intubated with a cuffed endotracheal tube (Portex®, I.D. 8 mm, length 26 cm) facilitated by intravenous administration of 60 mg of succinylcholine chloride. Subsequently, their anesthesia was maintained by 70% nitrous oxide and 30% oxygen, 10 mg of diazepam and 30 mg of pentazocine and they were paralyzed with intravenous administration of 4 mg of pancuronium bromide and ventilated mechanically. Airway pressure was measured by a pressure transducer and recorded by a recorder (Nihon Koden Co.). Then, a manually controlled constant flow generator was attached via a pneumotachograph (Nihon Kohden Co. MFP 1100) to the patient's endotracheal tube. Airway pressure, respiratory airflow and lung volume, which was calculated from integration of the airflow, were recorded simultaneously. At first, the lung was inflated stepwise 3 times by the constant flow generator with 0.5 l of of air being released each time. Prior to the inflation the flow was adjusted to either 0.5 $l \cdot sec^{-1}$ or 1.0 $l \cdot sec^{-1}$. Following the inflation, the lung was passively deflated. During deflation the expiratory flow was interrupted three times by an electric shutter at the points where the lung volumes were 1.5 l, 1.0 l and 0.5 l over functional residual capacity (FRC). During this expiration, the expiratory airflow was either unrestricted or restricted in three grades by an intentional airflow resistance attachment with values of 2, 5 and 10 $cmH_2O \cdot l^{-1} \cdot sec$. Airway resistance was calculated in two different manners; namely, the change in airway pressure at the moment inflation was stopped or the expiratory flow was interrupted was divided by the corresponding airflow. Finally, the values of airway resistance measured by constant flow inflations were divided into 6 groups. First, they were divided into two groups based on the airflow and then both groups were subdivided into three groups, respectively, based on the three measuring points. Data from the airway interuption, on the other hand, were treated as follows: the three values of airway resistance obtained from the three measuring points were plotted against the airflow, and a regression equation ($Y = K_1 + K_2X$) was obtained by the least squares method. Thus K_1 and K_2 were obtained as flow resistant constants.

The endotracheal tube used in this study (Portex®, I.D. 8 mm, length 26 cm) was attached to the pneumotachograph and pressure at the slipped joint of the endotracheal

Table 2. Airwary resistance measured during inspiratory phase with intermittent constant flow inflation in five subjects (the resistance of the endotracheal tube was included)

Subj. No.	n	inspirtory flow, $\mathrm{l\cdot sec^{-1}}$	L* $\mathrm{cmH_2O\cdot l^{-1}\cdot sec}$	M* $\mathrm{cmH_2O\cdot l^{-1}\cdot sec}$	H* $\mathrm{cmH_2O\cdot l^{-1}\cdot sec}$
1	16	0.49 ± 0.02	8.74 ± 1.83	6.93 ± 0.95	5.38 ± 1.03
	16	0.93 ± 0.03	10.95 ± 1.28	9.24 ± 1.00	6.86 ± 0.69
2	16	0.51 ± 0.04	7.11 ± 0.85	6.08 ± 0.57	5.17 ± 0.57
	16	0.91 ± 0.02	9.40 ± 0.62	8.42 ± 0.77	6.81 ± 0.88
3	16	0.53 ± 0.03	7.27 ± 0.59	6.62 ± 0.87	5.43 ± 1.19
	16	0.99 ± 0.02	10.70 ± 0.90	9.41 ± 0.55	8.56 ± 1.08
4	16	0.51 ± 0.03	6.99 ± 0.89	7.66 ± 1.20	7.90 ± 1.55
	16	0.94 ± 0.02	9.25 ± 0.50	8.10 ± 0.85	7.92 ± 1.51
5	16	0.48 ± 0.03	7.18 ± 1.08	6.48 ± 0.80	5.66 ± 0.83
	16	0.94 ± 0.02	11.20 ± 0.47	9.87 ± 0.65	8.56 ± 0.94
Mean ± SD	80	0.50 ± 0.03	7.36 ± 1.16	6.75 ± 1.03	5.96 ± 1.49
	80	0.94 ± 0.04	10.20 ± 1.10	8.99 ± 1.00	7.81 ± 1.30

* L, M, H: measured at 0.45 ± 0.06 l, 0.97 ± 0.07 l, 1.53 ± 0.08 l above FRC, respectively.

Table 3. Values of K_1 and K_2 measured in five subjects (the resistance of the endotracheal tube was included)

Subj. No.	n	K_1, $\mathrm{cmH_2O\cdot l^{-1}\cdot sec}$	K_2, $\mathrm{cmH_2O\cdot l^{-2}\cdot sec^2}$	r
1	16	5.67 ± 1.30	3.54 ± 1.47	0.954 ± 0.052
2	16	3.71 ± 1.15	5.99 ± 1.59	0.962 ± 0.041
3	16	3.76 ± 2.01	7.87 ± 2.69	0.973 ± 0.041
4	16	2.58 ± 0.78	5.70 ± 1.23	0.982 ± 0.019
5	16	3.68 ± 1.73	5.47 ± 3.26	0.976 ± 0.029
Mean ± SD	80	3.88 ± 1.74	5.71 ± 2.55	0.969 ± 0.039

tube was measured during several constant flows. The flow resistant constants of the endotracheal tube were also obtained by the least squares method. The resistance of another tube, the length of which was 13 cm including the slipped joint, and the resistance of the slipped joint alone were also measured in the same fashion.

The Student's t test and the paired t test were used for the statistical analysis.

Results

1. Airway resistance measured by constant flow inflation

As shown in table 2, the mean values of airway resistance measured with low flow (0.50 ± 0.03 $\mathrm{l\cdot sec^{-1}}$) were 7.36 ± 1.16 $\mathrm{cmH_2O\cdot l^{-1}\cdot sec}$ at low lung volume (0.45 ± 0.06 l above FRC), 6.75 ± 1.03 $\mathrm{cmH_2O\cdot l^{-1}\cdot sec}$ at middle lung volume (0.97 ± 0.07 l above FRC), and 5.96 ± 1.49 $\mathrm{cmH_2O\cdot l^{-1}\cdot l^{-1}\cdot sec}$ at high lung volume (1.53 ± 0.08 l above FRC)). With high flow (0.94 ± 0.04 $\mathrm{l\cdot sec^{-1}}$), they were 10.20 ± 1.10 $\mathrm{cmH_2O\cdot l^{-1}\cdot sec}$, 8.99 ± 1.00 $\mathrm{cmH_2O\cdot l^{-1}\cdot sec}$ and 7.81 ± 1.30 $\mathrm{cmH_2O\cdot l^{-1}\cdot sec}$, respectively.

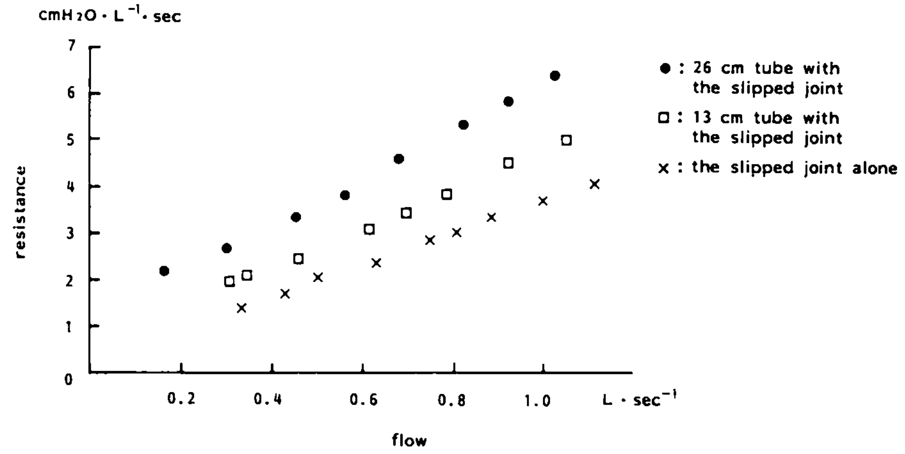

Fig. 1. Flow-resistance relationship of the endotracheal tube with its slipped joint.

•: Portex® tube, I.D. 8 mm, the length was 26 cm, □: the length of the tube was 13 cm, ×: slipped joint alone. The values of K_1 were 1.2, 0.6 and 0.3 $cmH_2O \cdot l^{-1} \cdot sec$, respectively. The values of K_2 were 5.0, 4.2 and 3.4 $cmH_2O \cdot l^{-2} \cdot sec^2$, respectively.

Table 4. Values of K_1 and K_2 measured adding each intentional resistance loading (the resistance of the endotracheal tube was included)

loading resistance, $cmH_2O \cdot l^{-1} \cdot sec$	n	K_1 $cmH_2O \cdot l^{-1} \cdot sec$	K_2 $cmH_2O \cdot l^{-2} \cdot sec^2$	r
0	20	4.22 ± 2.05	5.71 ± 2.85	0.953 ± 0.053
2	20	3.87 ± 1.97	5.72 ± 2.91	0.982 ± 0.026
5	20	3.56 ± 1.49	5.83 ± 2.04	0.974 ± 0.035
10	20	3.86 ± 1.44	5.58 ± 2.49	0.967 ± 0.032

In all subjects, the values measured at low lung volume were larger than those at middle lung volume ($P<0.01$), and those of middle lung volume were still larger than those at high lung volume ($P<0.01$). All the values of the low flow group measured at each lung volume were lower than those of the high flow group in all subjects ($P<0.01$).

2. Airway resistance measured by airway interruption during passive deflations

As shown in table 3, the airway resistances corresponding to the different flow rates had a highly linear relationship (r=0.969 ± 0.039). The mean values of K_1 and K_2 were 3.88 ± 1.74 $cmH_2O \cdot l^{-1} \cdot sec$ and 5.71 ± 2.55 $cmH_2O \cdot l^{-2} \cdot sec^2$, respectively. The values of K_1 and K_2 divided into four groups by the intentional loading of expiratory resistance are shown in Table 4. Neither K_1 nor K_2 was changed by any expiratory resistance loading.

As shown in figure 1, linear relationships between the airflow resistances of the endotracheal tube and airflows were also obtained. The K_1 value of the tube used in this study was 1.2 $cmH_2O \cdot l^{-1} \cdot sec$ and K_2 was 5.0 $cmH_2O \cdot l^{-2} \cdot sec^2$ (n=8, r=0.997). The K_1 value of the 13 cm long tube was 0.6 $cmH_2O \cdot l^{-1} \cdot sec$ and K_2 was 4.2 $cmH_2O \cdot l^{-2} \cdot sec^2$ (n=8, r=0.998). On the other hand, the K_1 and the K_2 values of the slipped joint alone were 0.3 $cmH_2O \cdot l^{-1} \cdot sec$ and 3.4 $cmH_2O \cdot l^{-2} \cdot sec^2$, respectively (n=9, r=0.999).

Discussion

The so-called "resistance" which exists in the airway tract consists of 3 components;

i.e., "airway resistance", which is the resistance of the airway alone, "pulmonary resistance", which is the sum of airway resistance and lung tissue resistance, and "respiratory resistance", which is composed of the sum of pulmonary resistance and resistance of the chest wall. In this study, the values measured by either constant flow inflations or airway interruptions were recognized as airway resistance, since the pressure change at the moment inflation was stopped or the airway was interrupted was considered to represent the pressure difference between the large airway and the alveoli. Some investigators, however, have recognized the value measured by airway interruption as pulmonary resistance, since the pressure change they measured at the moment of airway interruption was estimated to be larger than the actual airway-alveolar pressure difference[4-6].

In an adult man, respiratory resistance is about 4 $cmH_2O{\cdot}l^{-1}{\cdot}sec$, pulmonary resistance is about 2 $cmH_2O{\cdot}l^{-1}{\cdot}sec$, and airway resistance, breathing through the mouth, is about 1.3 $cmH_2O{\cdot}l^{-1}{\cdot}sec$, when measured at resting lung volume and at a rate of change of volume of 0.5 $l{\cdot}sec^{-1}$ [7]. This condition for the measurement of airway resistance was originally employed in making measurements with a body plethysmograph. When this method was used, the pressure-flow relationship was observed on an oscillograph. If the flow was high, the pressure-flow relationship became an upwardly concave curve, presumably due to turbulence. The relationship between pressure and flow, however, seemed mostly linear at a flow of 0.5 $l{\cdot}sec^{-1}$. Therefore, airway resistance was calculated from the slope of the line[8-10]. Nowadays, for convenience sake, this measuring condition is widely accepted for the measurement of airway resistance even by other methods.

The data from intermittent constant flow inflations showed that the larger the flow was and the less the lung volume was, the higher the airway resistance was. This had been well-recognized previously[7], but the value measured with low flow at low lung volume was 7.35 ± 1.16 $cmH_2O{\cdot}l^{-1}{\cdot}sec$, which was quite a bit larger than the normal value. Rossi et al.[11] measured respiratory resistance in mechanically ventilated patients with respiratory failure by two methods, a constant flow inflation method and an end-inflation airway occlusion method. Their data were generally comparable with our results, but it remained unclear whether the high values they recorded were due to the disease per se or to the methods they employed.

An upwardly concave curve relationship has been experimentally confirmed to exist between airflow (F) and airway pressure (P)[6,12]. Rohrer[12] applied the equation of $P = K_1F + K_2F^2$ to the curve. Dividing both sides of this equation by F, a straight line relationship between airflow and airway resistance R (=P/F) was obtained. This linear relationship could be written in the following slope-intercept form: $R = K_1 + K_2F$, where K_2 is the slope and $(0,K_1)$ is the R intercept. This linear relationship between flow and airway resistance best fitted our results. The value of K_1 would be a part of airway resistance unrelated to airflow and the value of K_2 would show the degree of influence of airflow on airway resistance. Therefore, K_1 would be thought to be airway resistance arising by laminar flow and K_2 would be the degree of airway resistance arising by turbulent flow. Although this hypothesis has little theoretical basis, it is well-known that it corresponds to experimental observations[7]. By this expression of airway resistance, K_1 and K_2 are 1.2 $cmH_2O{\cdot}l^{-1}{\cdot}sec$ and 0.3 $cmH_2O{\cdot}l^{-2}{\cdot}sec^2$, respectively, in a normal man[13]. The upper airway resistance derived from the mouth to the pharynx has been estimated to make up 30 ~ 50% of the total airway resistance[14-16]. However, an endotracheal tube was substituted for the upper airway in our study. To exclude the influence of the endotracheal tube, we measured the K_1 and K_2 values of the endotracheal tube. As shown in figure 1, the K_1 value of the tube was 1.2 $cmH_2O{\cdot}l^{-1}{\cdot}sec$. Since the K_1 value was thought to be additive if K_1 arose by laminal flow, the K_1 value of the lower airway in our five subjects was 2.68 ± 1.74 $cmH_2O{\cdot}l^{-1}{\cdot}sec$. On the other hand, there was no regular relationship between the K_2

value of the tube and the K_2 value of the airway resistance measured in our five subjects. As the influence of the endotracheal tube on the K_2 value of the airway resistance seems to be quite complicated, the K_2 value of the tube and that of the lower airway resistance could not be distinguished from each other. Moreover, as Behrakis et al.[17] also discovered, the K_2 value of the endotracheal tube including its slipped joint is fairly high; i.e. it was 5.0 $cmH_2O \cdot l^{-2} \cdot sec^2$ in our study and 8.6 $cmH_2O \cdot l^{-2} \cdot sec^2$ in theirs. The difference between the value of our study and that of Behrakis et al. may have been produced by a difference in the length of the tubes or in the shape of the slipped joints. Therefore we reached the conclusion that the airway resistance of the lower airway measured in intubated subjects should be expressed as the K_1 value alone. The concept of the K_1 value seemed to be similar to V_{max}, which was the unloaded maximum contractile velocity for expressing myocardial contractility used by Mason et al.[18]

The measurement of airway resistance in anesthetized and paralyzed subjects seems much easier than in conscious patients since the cooperation of the subject is not necessary and the influence of voluntary muscles on the measurement should be excluded. Nevertheless, there have been few studies in which airway resistance has been measured via an endotracheal tube. Bergman[19] measured the respiratory resistance in 12 subjects under anesthesia with GOF and paralysis by dTc. In that study, K_1 and K_2 were reported to be 4.1 ± 0.4 $cmH_2O \cdot l^{-1} \cdot sec$ and 2.2 ± 0.3 $cmH_2O \cdot l^{-2} \cdot sec^2$, respectively. The value of K_1 seemed to mostly correlate with our results. But Bergman's K_2 was lower than ours. The difference in the K_2 values may be due to the endotracheal tube. Bergman used a bigger endotracheal tube, the inner diameter of which was reported to be 10 mm. Behrakis et al.[17] measured the respiratory resistance in 6 subjects during GOF anesthesia either with or without muscle paralysis by dTc. Then the value of K_1 for the lower airway was determined to be 1.6 ± 0.7 $cmH_2O \cdot l^{-1} \cdot sec$ in the non-paralyzed state and 1.9 ± 0.9 $cmH_2O \cdot l^{-1} \cdot sec$ in the paralyzed state. These values were quite a bit lower than ours. They measured the respiratory resistance by airway occlusion at end-inspiration. We, on the other hand, measured airway resistance by airway interruptions during passive deflations. Since respiratory resistance contains lung tissue resistance and chest wall resistance in addition to airway resistance, respiratory resistance should be larger than airway resistance. Nevertheless, the K_1 value of Behrakis was lower than ours. This, however, may be due to the difference in the measuring method.

It is very important that the values of K_1 and K_2 value obtained by this method were not altered by intentional loading of expiratory resistance. In other words, other measurements, such as simultaneous expiratory gas sampling with a Douglas bag will not distort the measurement of airway resistance, and the K_1 value obtained in this method may be useful in expressing the lower airway resistance measured via an endotracheal tube.

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