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ENGINEERING PERFORMANCE EVALUATION OF ARMY VOLUME-CYCLED RESPIRATOR, MODEL 3

by

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ABSTRACT

The Army volume-cycled respirator, which has pressure-cycling capabilities, can assist or control the ventilation of patients. The Model 3 respirator was designed to reduce the internal compliance that caused undesirable performance in the Model 2 unit. Engineering tests using simulated lung compliances and airway resistances show that internal compliance has been reduced from about 0.010 ℓ/cm H_2O in Model 2 to about 0.002 ℓ/cm H_2O in Model 3. Consequently, the variation in delivered tidal volumes due to changes in simulated patient compliance and resistance is much less in Model 3 than in earlier models.

The complete engineering performance of the Model 3 respirator, including inspiratory times, expiratory times, cycling rates, delivered tidal volumes, minute volumes and mask pressures, are presented. Generally the results show that this respirator has a wide range of performance and is capable of giving adequate ventilation for all test conditions studied.

CONTENTS

FIGURES

1. INTRODUCTION

The Army volume-cycled respirator (fig. 1, 2) is a joint development of the Harry Diamond Laboratories (HDL) and the Walter Reed Army Institute of Research (WRAIR). It is powered and controlled by two bistable fluid amplifiers. The respirator is designed to either assist or control a patient's ventilation, and it may be pressure-cycled as well as volume-cycled. The power circuit and patient circuit are separated to permit the use of contaminated (not suitable for breathing) compressed gases as the power source. The oxygen content in the breathing gas may be varied between 20 (air) and 100 percent.

Earlier models of this respirator[1,2] exhibited large variations in delivered tidal volumes produced by changing the load presented to the respirator. The problem was caused by excessive internal compliance in the respirator, primarily due to radial expansion of the rubber bellows. In the Model 3 unit, this internal compliance has been reduced to a more acceptable level, so that tidal volumes are no longer severely affected by changes in simulated patient compliance and/or airway resistance.

This report presents the complete engineering performance evaluation of the Model 3 respirator.

2. DESIGN REQUIREMENTS

The current requirements for this respirator are based on the premise that the respirator will be used primarily on adult patients. Further, these requirements have been generated with emphasis on the needs of Army medicine.

The requirements[2] are as follows:

(1) The respirator should be able to assist or control the ventilation of a patient, and the change from one mode of operation to the other should take place automatically.

(2) In the assist mode of operation, the respirator should be able to sense an inspiratory effort by the patient of 1.0 cm H_2O negative pressure. Sensitivity of the inspiration initiation trigger should, in addition, be variable at least to 4 cm H_2O of negative pressure.

(3) The respirator should have pressure-cycling capabilities. The switching pressures for the pressure-cycled mode of operation should be continuously variable between 10 and 60 cm H_2O.

(4) The respirator should have a continuously variable tidal volume capability from 300 to 2500 cc.

(5) The respirator should be able to deliver minute volumes from 5 to 20 ℓ/min.

[1] Joyce, J. W., "The Development of a Volume-Cycled Respirator," HDL TM-65-14, 24 March 1965.

[2] Joyce, J. W., "Revised Performance Evaluation of the Army Volume-Cycled Respirator, Model 2," HDL TM-68-17, July 1968.

(6) When operating in the control mode, the respirator should be able to cycle from 6 to 60 cpm.

(7) The inspiratory period of the respirator should be continuously variable from 0.4 to 2.0 sec.

(8) Expiratory periods achieved by the device should be compatible with the requirements for inspiratory times and cycling rates stated above.

(9) The respirator must be able to administer breathing gas of variable oxygen content.

(10) The respirator should have a gas canister to filter contaminated incoming air when room air is used as the breathing gas.

(11) Provisions must be made to humidify the breathing gases being administered to the patient.

3. OPERATIONAL DESCRIPTION

Figure 3 is a schematic diagram of the respirator. The two fluid amplifiers are operated through a common pressure regulator. At the beginning of a cycle, the output of amplifier A (located on the front of the respirator) is flowing into the lower piston chamber, pushing the piston upward, while the output of amplifier B (located on the back of the respirator) is exhausting to the surroundings. As the piston is driven upward, the rubber bellows is compressed, and breathing gas in the bellows is forced into the patient's lungs via the breathing valve. In the normal volume-cycled mode of operation, the upward motion of the piston is terminated when a striker attached to the bottom of the bellows activates a mechanical (upper excursion) trigger. Activation of this trigger opens feedback lines to both fluid amplifiers and switches them simultaneously, so that the output of amplifier B is now flowing into the upper piston chamber, driving the piston down, and the output of amplifier A exhausts to the surroundings. In the pressure-cycled mode of operation, piston upstroke is terminated when a predetermined pressure is reached in the patient circuit. This pressure activates the pressure-cycle trigger (a spring-loaded diaphragm arrangement), and as in the case of volume-cycled operation, feedback lines to both amplifiers are opened to admit switching air flow, and the amplifiers are switched to begin the downstroke.

As the piston descends, the bellows refills with fresh breathing gas through a one-way valve in the gas intake at the top of the respirator. The patient, meanwhile, exhales to the surroundings through the breathing valve. None of the exhaled gases are allowed to reenter the bellows where they could be breathed again. At the bottom of the downstroke, the bottom of the bellows strikes an adjustable mechanical (lower excursion) trigger, and in so doing, opens the left feedback line to amplifier B. This action switches the amplifier's power stream to the right receiver where it exhausts to the surroundings. Amplifier A is not affected by this trigger, and its output continues to exhaust. At the instant the bellows comes to rest at the bottom of the downstroke (but not until such time), the rate of entrainment out of the lower piston chamber produced by the exhausting amplifier A is sufficient to produce negative (below ambient) pressure in this chamber. The negative pressure operates the delay mechanism by exerting a pulling force on one side of a small piston. The rate of motion of the delay piston is controlled by a variable atmospheric bleed (a needle valve) that determines the retarding force on the other side of this piston. Consequently, a variable time delay is achieved, since the stroke of the delay piston is fixed. In the control mode of operation, when the delay piston has completed its stroke, it strikes a mechanical trigger that opens the right feedback line to amplifier A, thereby switching its power stream back into the driving piston chamber to begin a new cycle. In the assist mode, an inspiratory attempt by the patient, in the form of a small negative pressure, initiates a new cycle by activating the inspiration initiation trigger before the delay time has completely elapsed. The inspiration initiation trigger is also a spring-loaded diaphragm arrangement which, when activated, opens the right feedback line to amplifier A to switch it and begin a new cycle.

The makeup of the breathing gas entering the bellows each cycle is determined by the setting of the air-oxygen mixing valve attached to the intake at the top of the respirator (fig. 1). This valve, which is described in detail in HDL-TM-69-20[3], is calibrated to deliver gas mixtures containing 20, 30, 40, 50, 60, 70, 85 or 100 percent oxygen.

The difference in operation between this respirator and the previous (Model 2) respirator is that here the lower excursion trigger is adjustable and the upper excursion trigger is fixed, whereas in the Model 2 unit, the upper trigger was adjustable and the lower one was fixed. Fixing the upper trigger insures that the bellows is completely collapsed (axially) at the end of each inspiratory phase. As a result, the bellows cannot expand radially to any great degree, and the compliance of the Model 3 respirator is much less than that encountered in the Model 2 unit. Data to support this statement will be presented later.

In this prototype of the Model 3 respirator, adjustment of the lower excursion trigger was accomplished by a system of gears and racks used together with a positive locking crank system that produced discrete changes in the position of the trigger. Consequently, continuous adjustment of tidal volume is not possible in this prototype. Future prototypes would be designed to permit continuous changes in tidal volume settings.

The functions of the various controls in altering the parameters involved are discussed later.

4. TEST EQUIPMENT AND PROCEDURE

To determine the performance capabilities of the respirator, it was necessary to simulate lung compliance and airway resistance. Lung compliance was simulated by fixed volume tanks[4]. A 19-mm long

[3] Joyce, J. W., "An Air-Oxygen Mixing Valve for Volume-Cycled Respirators," HDL TM-69-20, August 1969.

[4] Saklad, M. and Wickliff, D., "Functional Characteristics of Artificial Ventilators," Anesthesiology, Vol. 28, No. 4, July - August 1967.

cylinder with 0.8-mm diameter holes drilled through it was inserted in the tubing connecting the respirator to the tank (compliance) to simulate airway resistance.

The compliances of the tanks were experimentally determined by injecting known volumes of air into them and recording the peak pressures developed. The average measured values of compliance were 0.010, 0.026, 0.053, and 0.111 ℓ/cm H_2O for the tanks used in testing the respirator.

Different values of airway resistance were obtained by controlling the number of holes that were open in the cylinder. For each hole pattern selection, the resistance was calibrated by first measuring pressure drops across the cylinder for various flow rates of air through it. The pressure drop divided by the corresponding flow rate was then plotted versus flow rate. From the resulting straight lines, the constants k_1 and k_2 in the equation

$$\Delta P = k_1 Q + k_2 Q^2$$

where

$$\Delta P = \text{pressure drop, cm } H_2O$$

$$Q = \text{flow rate, } \ell/\text{sec}$$

were determined graphically. The resulting values are shown in table I. The resistance R_o represents no resistance (cylinder not placed in test circuit). Defining airway resistance as the pressure drop per unit flow rate evaluated at $Q = 1$ ℓ/sec, it then becomes equal to $(k_1 + k_2)$. These values are also shown in table I.

For each combination of compliance and resistance, the respirator was operated at various tidal volumes. For each tidal volume setting, the respirator was run at the minimum input air pressure needed to cycle the respirator, and also at an input pressure of 210 kN/m^2 (30psig), which is the upper design limit.

A pressure transducer (±70 cm H_2O range) was used to sense pressures in the tanks and ahead of the airway resistance. The latter measurement represents face-mask pressure, which is the pressure monitored by most respirators. A second transducer (±100 kN/m^2 range) was used to monitor pressures in the right feedback line of amplifier B to determine the downstroke and delay times. These two durations cannot be measured from tank pressures, which indicate only the total expiratory time (the sum of downstroke and delay times). The outputs of the transducers were displayed on a storage oscilloscope from which the data were recorded.

Table I. Airway Resistances

	k_1	k_2	$(k_1 + k_2)$
R_o	0	0	0
R_1	5.8	13.3	19.1
R_2	9.3	34.7	44.0

5. PERFORMANCE RESULTS

5.1 Calibration of Tidal Volumes

The first step in the testing was to calibrate tidal volumes. As previously mentioned, tidal volume can be adjusted only in discrete steps in this prototype. This feature does, however, facilitate repeating the same volume settings for different test runs.

Tidal volumes were calibrated in the following manner. The respirator was connected to the 0.053-ℓ/cm H_2O compliance with no airway resistance. Bellows displacement was varied by the smallest increment (about 0.82 cm) produced by the crank mechanism. Maximum available stroke displacement was about 11.5 cm. At each volume setting, the respirator was operated at maximum and minimum input air pressures, and peak pressures developed in the compliance were recorded. Tidal volumes were then calculated from the definition of compliance, which is

$$C \equiv \frac{\Delta V}{\Delta p}$$

where

C = compliance, ℓ/cm H_2O

ΔV = tidal volume, ℓ

Δp = peak pressure developed in tank, cm H_2O

The results of this test are shown in figure 4 which plots delivered tidal volume versus arbitrarily numbered volume settings corresponding to the 0.82-cm bellows displacement increments. Figure 4 indicates that tidal volume is a linear function of bellows displacement. Each incremental change in bellows displacement produces a change in tidal volume of about 130 mℓ, and the maximum tidal volume available is about 1700 mℓ. Delivered volume is only slightly affected by respirator input pressure. Using the average values from these results, the tidal volume scale (expressed in mℓ) shown in figure 1 was engraved in the bellows cover.

5.2 Inspiratory Time

The inspiratory time can be varied by adjusting the input pressure to the respirator. Increasing the input pressure produces greater driving energies and therefore decreases inspiratory time. Inspiratory time increases as the volume setting is increased since a longer stroke must be completed. For a given input pressure and volume setting, inspiratory time depends on the load presented to the respirator. This is illustrated in figures 5 and 6. The curves indicate that inspiratory time increases as compliance decreases (fig. 5) and as airway resistance increases (fig. 6). The complete data for inspiratory times is given in appendix A.

5.3 Expiratory Time

The expiratory time for this respirator consists of the downstroke time during which the bellows refills, and the delay time during which the bellows pauses in the reset position. The entire expiratory phase is independent of patient loading (in the control mode of operation). Downstroke time depends on respirator input air pressure and tidal volume setting; the delay time is a function of input pressure only.

Figure 7 shows respirator downstroke times as a function of input pressure for various volume settings. The curves indicate that downstroke time decreases with increasing input pressure and decreasing volume settings. A comparison of downstroke times at 210-kN/m^2 (30-psig) input pressure with corresponding inspiratory times (apx A) reveals that downstroke times are slightly less than the corresponding inspiratory times. This is important because the function of the respirator is such that a breathing attempt from the patient cannot initiate a new cycle until the downstroke is complete. It is therefore desirable to keep the downstroke time as small as possible, and keeping it smaller than the inspiratory time at least minimizes the chance of the respirator's interfering with the patient's breathing rhythm when the respirator is operating in the assist mode.

The maximum and minimum delay times as a function of respirator input pressure are illustrated in figure 8. Delay times from about 0.5 to 60 sec can be achieved. It is during this delay phase of the cycle that assist efforts from the patient can initiate a new breathing cycle. The delay control is used to vary expiratory time, since this control can be adjusted without affecting the other parameters.

5.4 Cycling Rates

From the data for inspiratory and expiratory times, the maximum and minimum cycling rates for the respirator can be calculated. Because of the long delay times available (fig. 8), the minimum cycling rates are less than 3 cpm for all test conditions. The maximum rates will be influenced by loading and the volume setting selected, inasmuch as inspiratory and downstroke times are affected by these parameters. Figures 9 and 10 show the effects of compliance and airway resistance on maximum respirator cycling rates over the range of volume settings. Maximum rate decreases as compliance decreases and as airway resistance increases. The complete data for maximum cycling rates are given in appendix B.

All data for cycling rates are a measure of respirator capability only; they do not consider the possibility of trapping. The term trapping refers to a condition where the expiratory time of the respirator is insufficient to allow all the tidal volume delivered during inspiration to be exhaled to the ambient surroundings (passive exhalation). Consequently, some of the tidal volume is trapped, and such a condition reduces the efficiency of ventilation by increasing the volume of residual gas in the lungs. In actual practice, the maximum cycling rate may therefore be limited by the condition of the patient rather than by the capabilities of the respirator.

5.5 Delivered Tidal Volumes

As mentioned earlier, the large internal compliance of the Model 2 respirator produced large variations in tidal volumes with changes in simulated patient compliance and airway resistance.[5] In some cases, delivered volumes differed from the calibrated values by as much as 50 percent. The internal compliance of the Model 2 respirator was determined to be about 0.010 ℓ/cm H_2O.

For the Model 3 respirator, the range of delivered tidal volumes over all test conditions imposed on the respirator is illustrated in figure 11, and the complete data for delivered volumes are given in appendix C. Delivered volumes were calculated from peak pressures developed in the compliance as explained in section 5.1. For the 0.010-ℓ/cm H_2O compliance with the highest airway resistance (R_2), delivered volumes are about 20 percent below the calibrated values. For all other compliances with all resistances, however, the delivered volumes do not vary from the calibrated values by more than 10 percent and this error is only for the two smallest volume settings. The error at the other ten settings is about 5 percent or less. Based on these data, the internal compliance of the Model 3 respirator appears to be about 0.002 ℓ/cm H_2O. Therefore, internal compliance has been significantly reduced — to the point where it should not seriously interfere with respirator performance except possibly under the most severe load conditions.

5.6 Minute Volumes

The minute volume delivered by the respirator is, by definition, the product of delivered tidal volume and cycling rate. Because the minimum cycling rates are very low (sect. 5.4), the minimum minute volumes are about 3.5 ℓ/min or less for all conditions. The maximum available minute volume increases with increasing compliance (fig. 12) and decreases with increasing airway resistance (fig. 13). The complete data are tabulated in appendix D. Except for a few values at the small volume settings, all minute volumes are 20 ℓ/min or greater, which indicates that the respirator can easily provide adequate ventilation under all load conditions.

5.7 Pressures Ahead of Resistance

The pressure developed ahead of the airway resistance corresponds to face-mask pressure or the pressure monitored by most respirators. This pressure depends on the airway resistance and the flow rate through it. Figure 14 illustrates the effect of airway resistance on this pressure for maximum inspiratory times (slowest inspiratory flow rates). Pressure ahead of the resistance increases as the resistance increases, but the increases are not large compared with those in figure 15, which shows the results for the minimum inspiratory times (fastest inspiratory flow rates). In the upper curve in figure 15, pressures are between 40 and 60 cm H_2O for all but one of the volume settings, while the corresponding pressures in the compliance (the lower curve for R_O) are between 5 and 30 cm H_2O. These pressures illustrate the potential problem associated with pressure-cycled operation when operating on a patient with high airway resistance. Mask pressures may be very high,, but this pressure alone gives no indication of how much air is reaching the lungs.

The complete data for pressures ahead of the airway resistances are presented in appendix E.

[5]Joyce, HDL-TM-68-17, op cit.

5.8 Other Functions

The pressure-cycle trigger and assist sensitivity of the inspiration initiation trigger in the Model 3 respirator are unchanged from those in the Model 2 unit. As before, pressure cycling between 10 and 60 cm H_2O can be achieved. Assist sensitivity can be varied from about 1 to 4 cm H_2O of negative (below ambient) pressure.

Similarily, the power consumption is the same as for the Model 2 respirator. Maximum air flow consumed is 61 ℓ/min of free air at the upper limit input pressure of 210 kN/m^2 (30 psig).

6. SUMMARY

The performance results of the Model 3 respirator show conclusively that the problem of internal compliance associated with the Model 2 unit has been significantly reduced. Total variation in tidal volumes with different compliance-resistance combinations is only a fraction of that exhibited by previous models. All other functions are basically the same as for earlier models.

Other minor changes and additions to the respirator have increased its potential usefulness. The air-oxygen mixing valve that permits the selection of breathing gas containing oxygen concentrations of 20 to 100 percent was not available with the other models. The standard expiratory port added to the breathing valve permits a spirometer or other device to be easily attached.

The Model 3 respirator will be medically evaluated at WRAIR to determine overall effectiveness. If results of the this testing warrant further development, there are a number of design improvements that can be made, including a continuously adjustable tidal volume selector and simplified packaging.

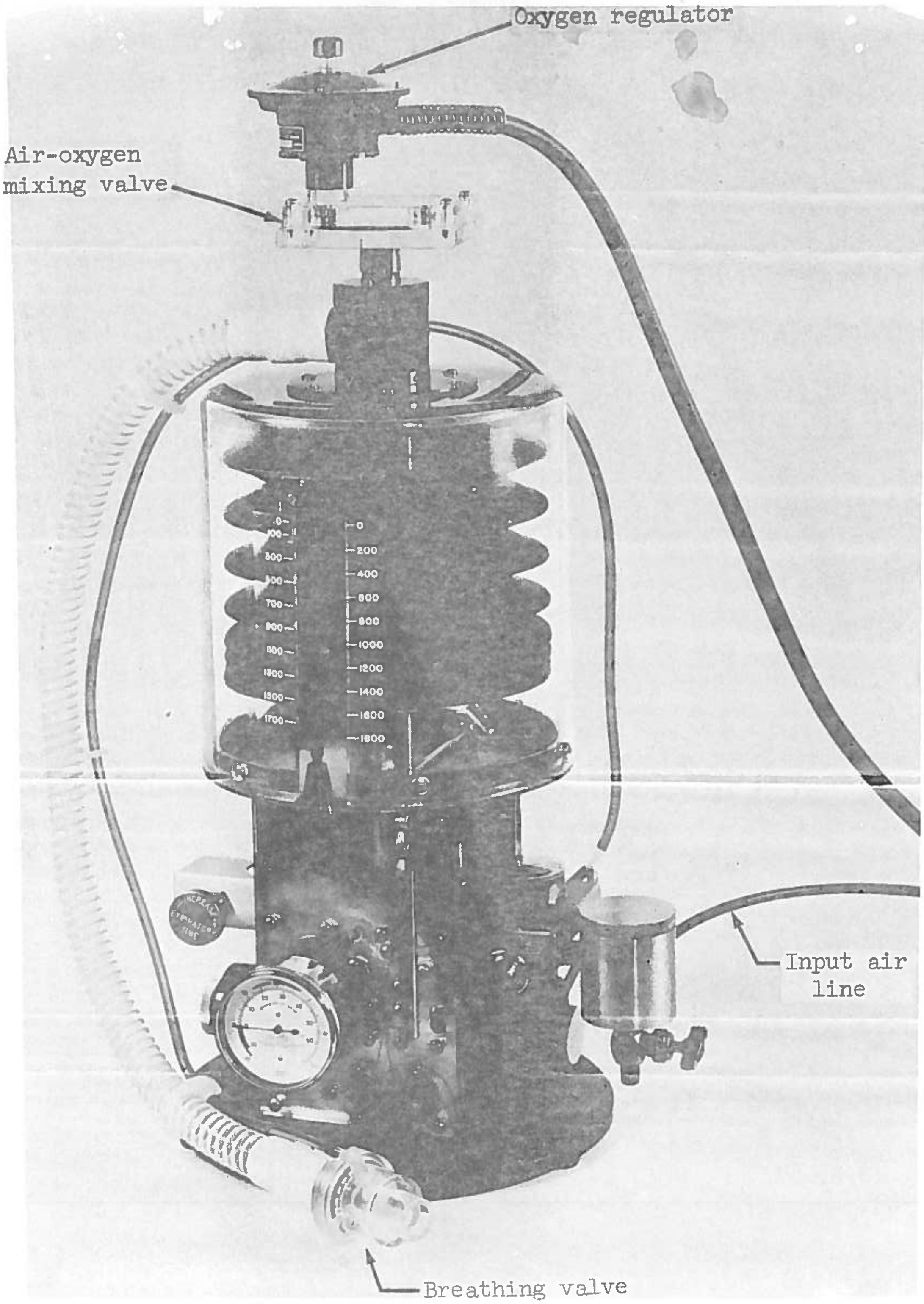

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Figure 1. Army volume-cycled respirator, front view.

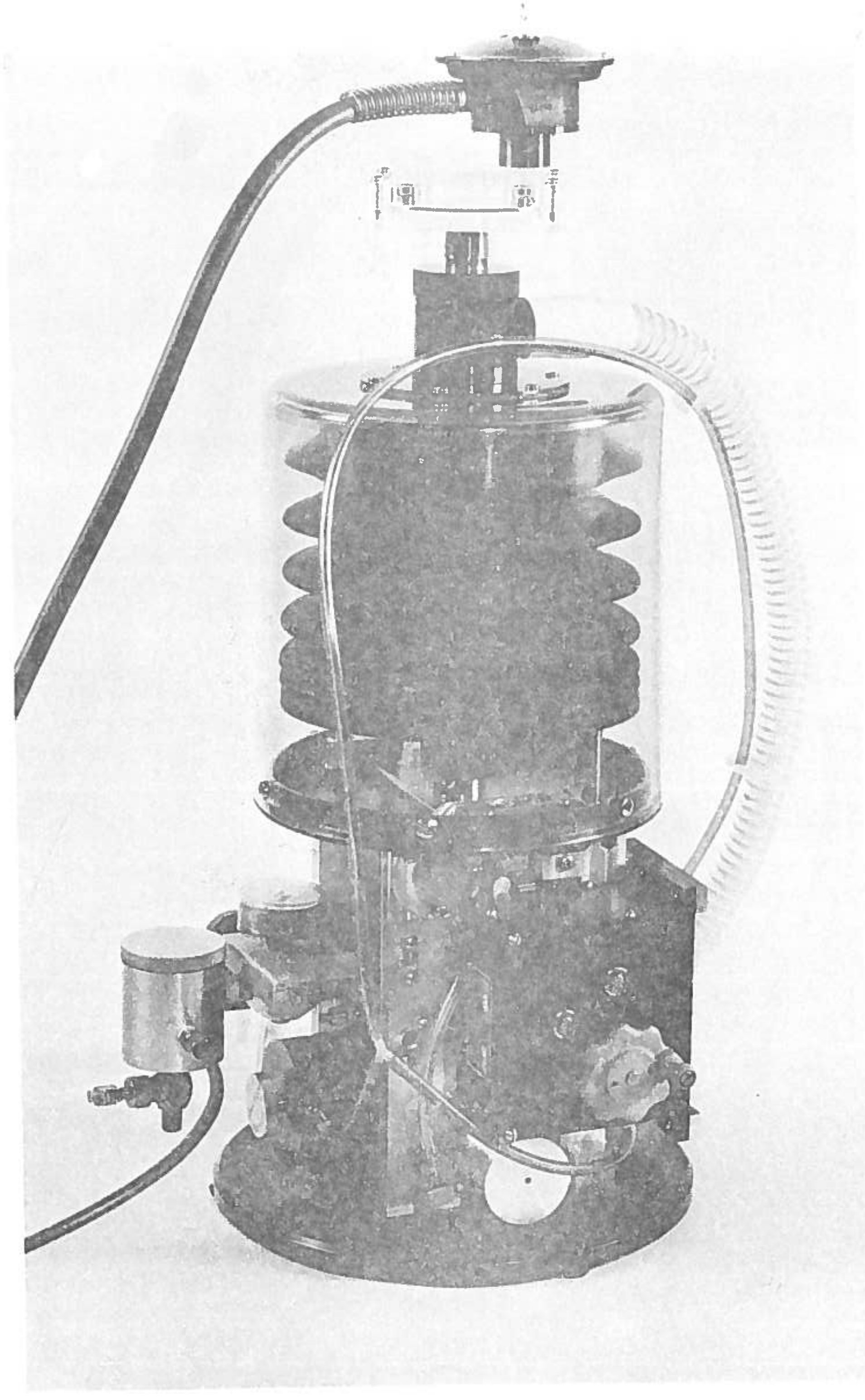

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Figure 2. Army volume-cycled respirator, rear view.

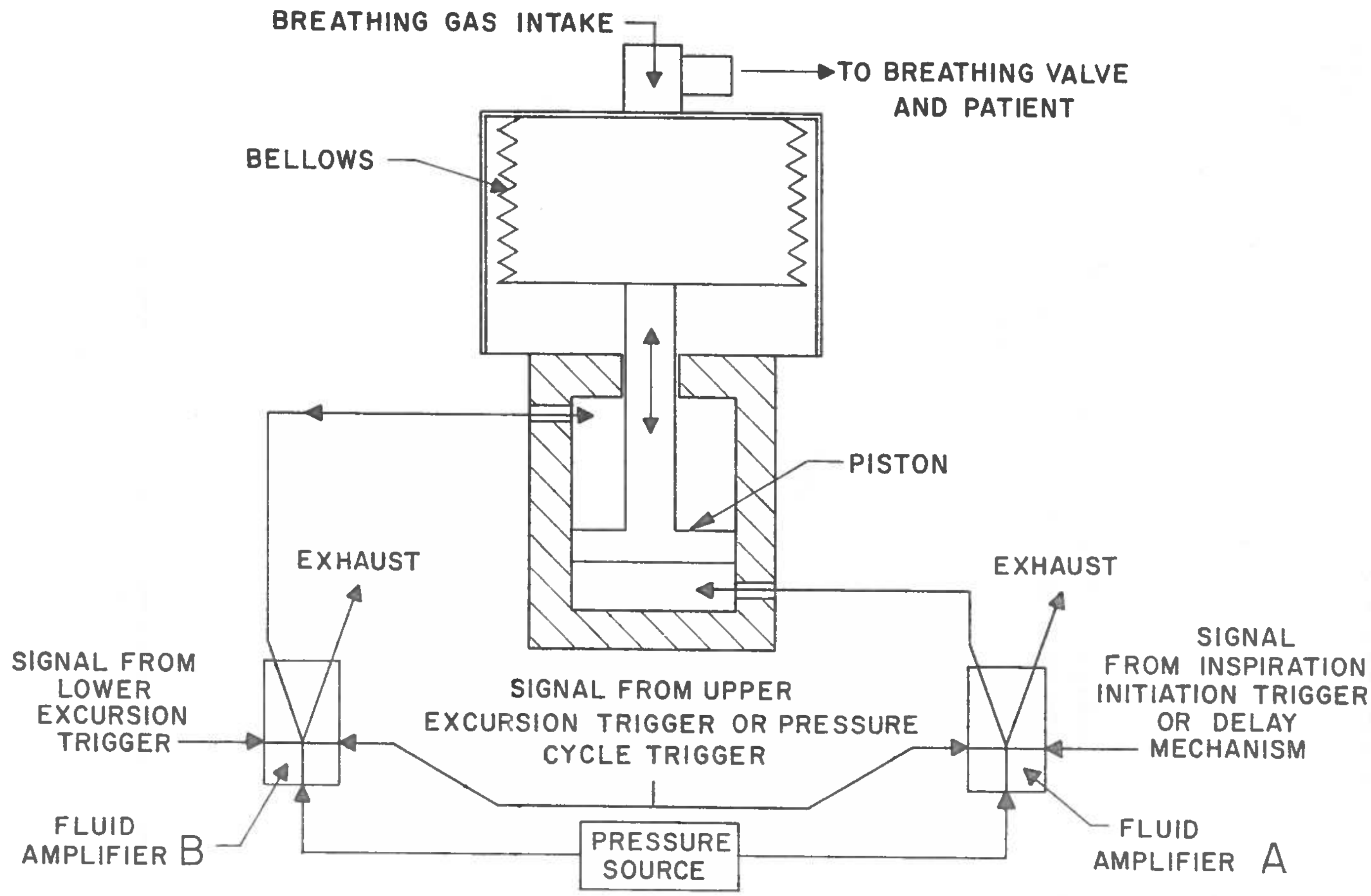

Figure 3. Schematic diagram of volume-cycled respirator.

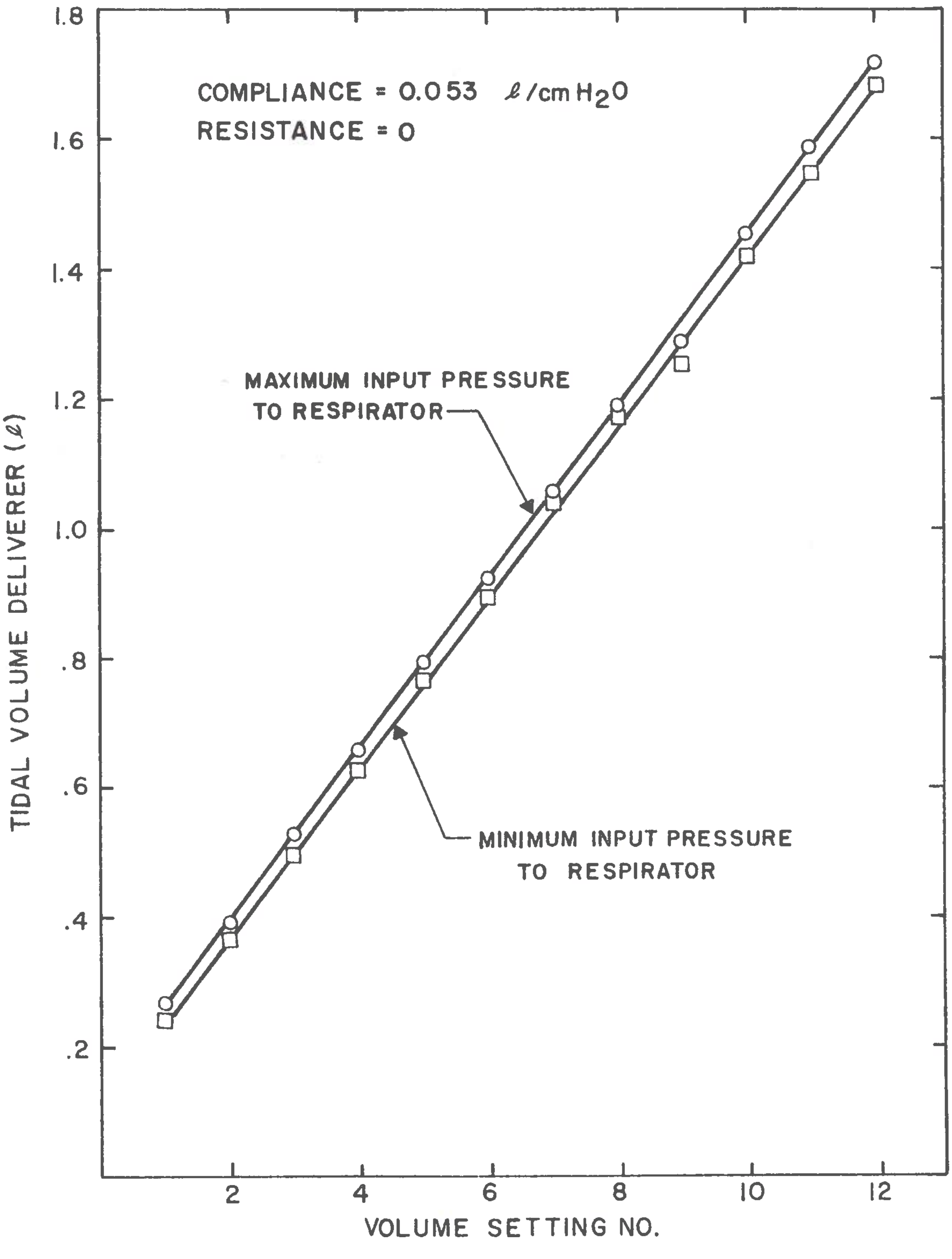

Figure 4. Tidal volume calibration.

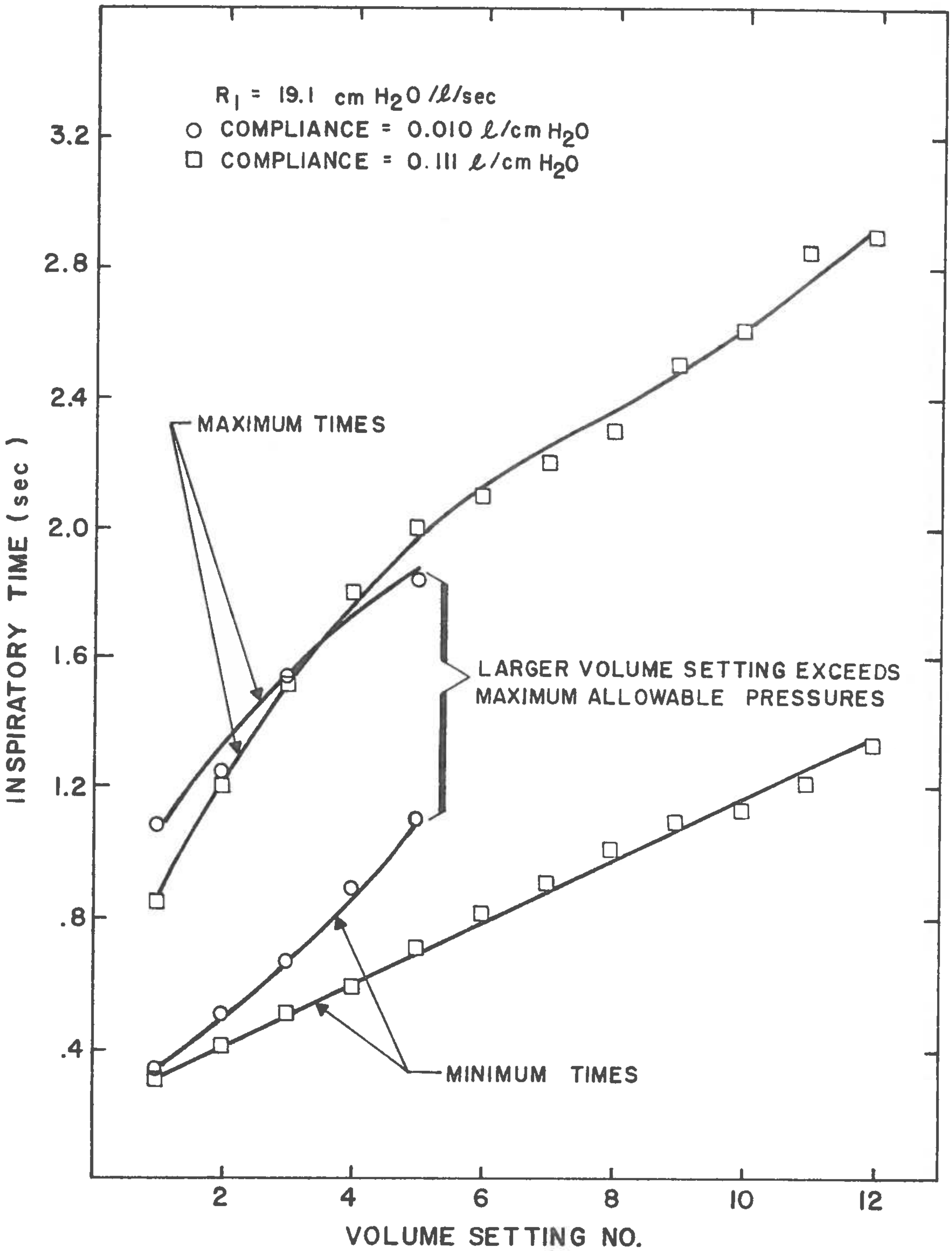

Figure 5. Effect of compliance on inspiratory time.

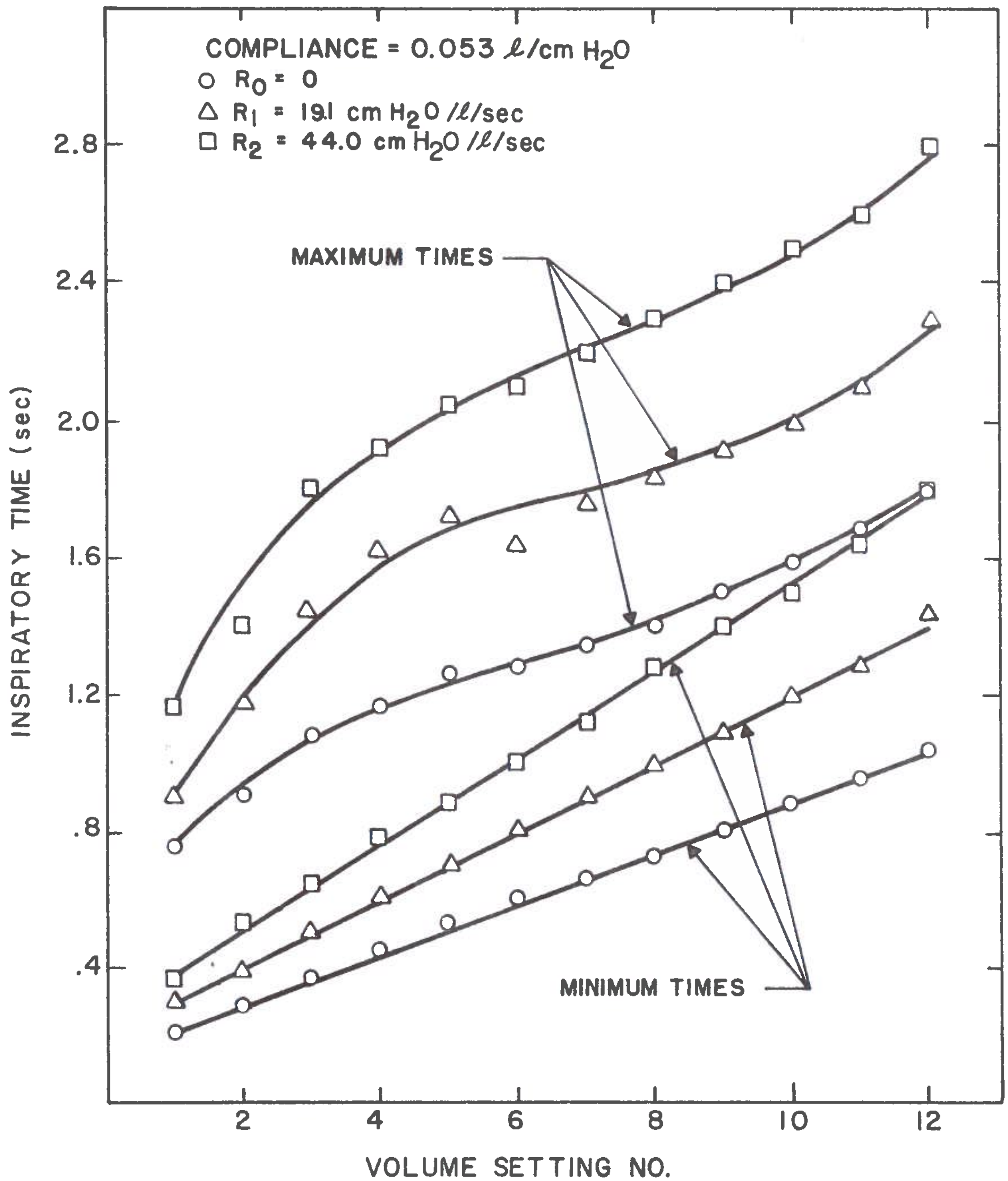

Figure 6. Effect of airway resistance on inspiratory time.

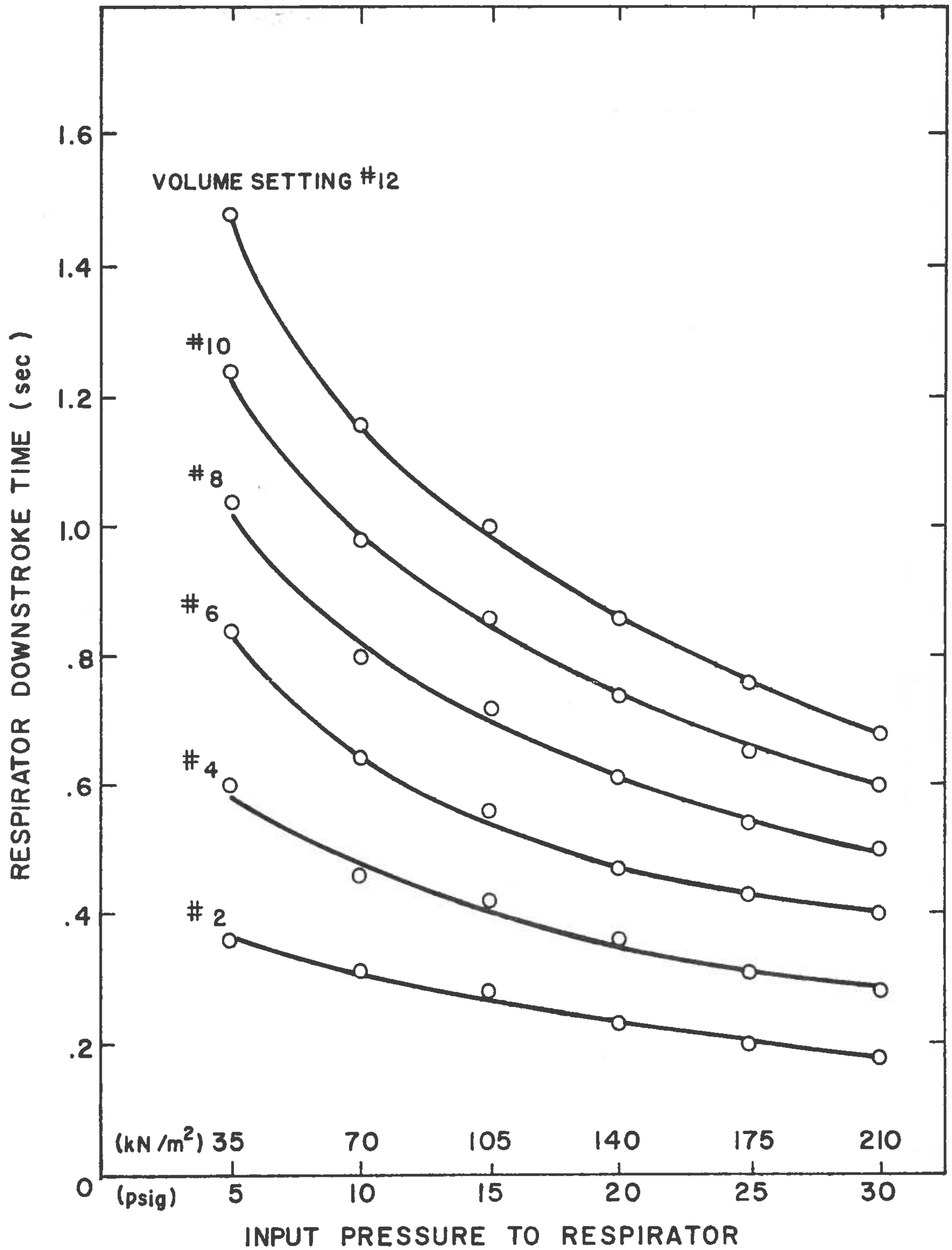

Figure 7. Respirator downstroke times.

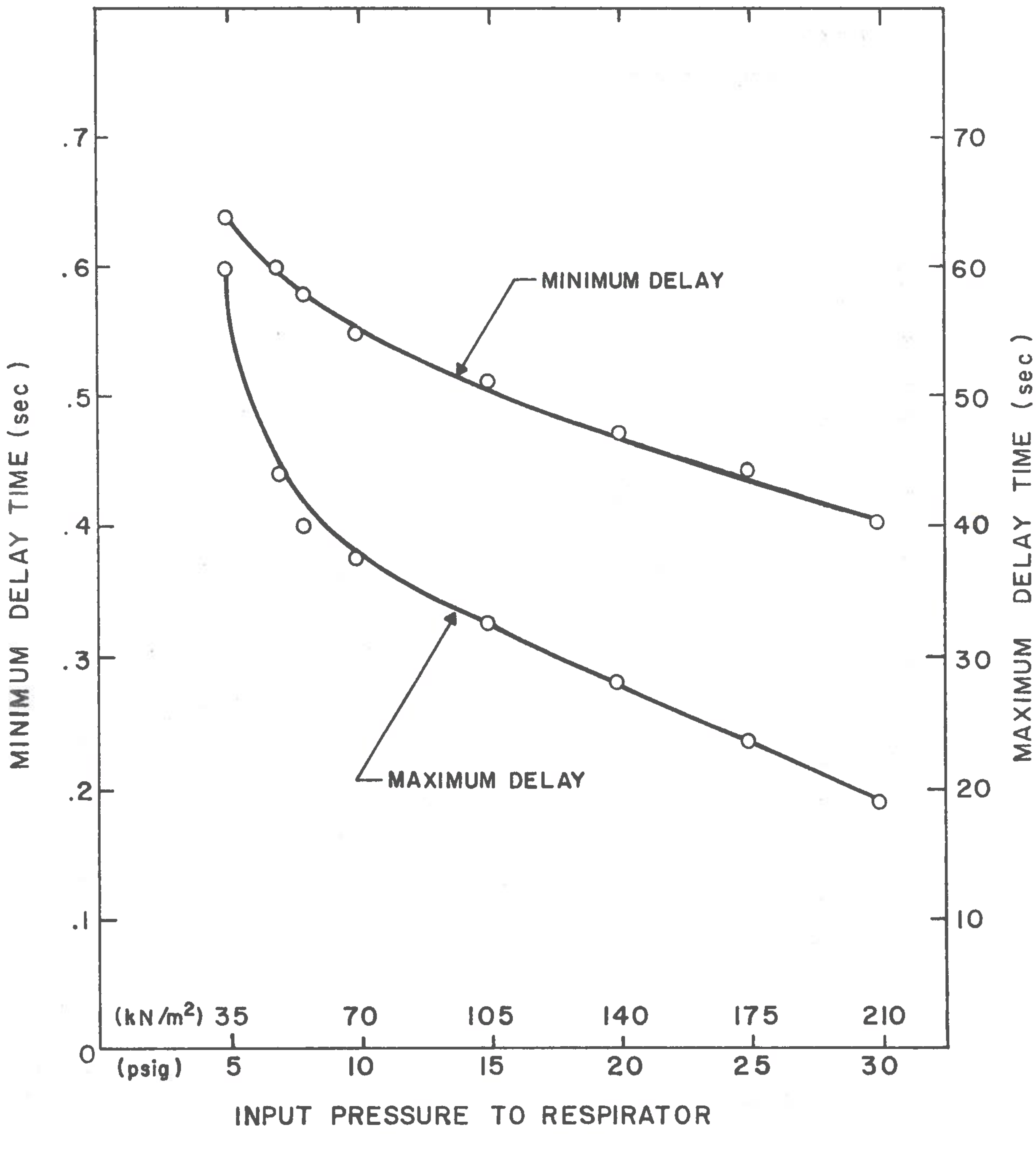

Figure 8. Respirator delay times.

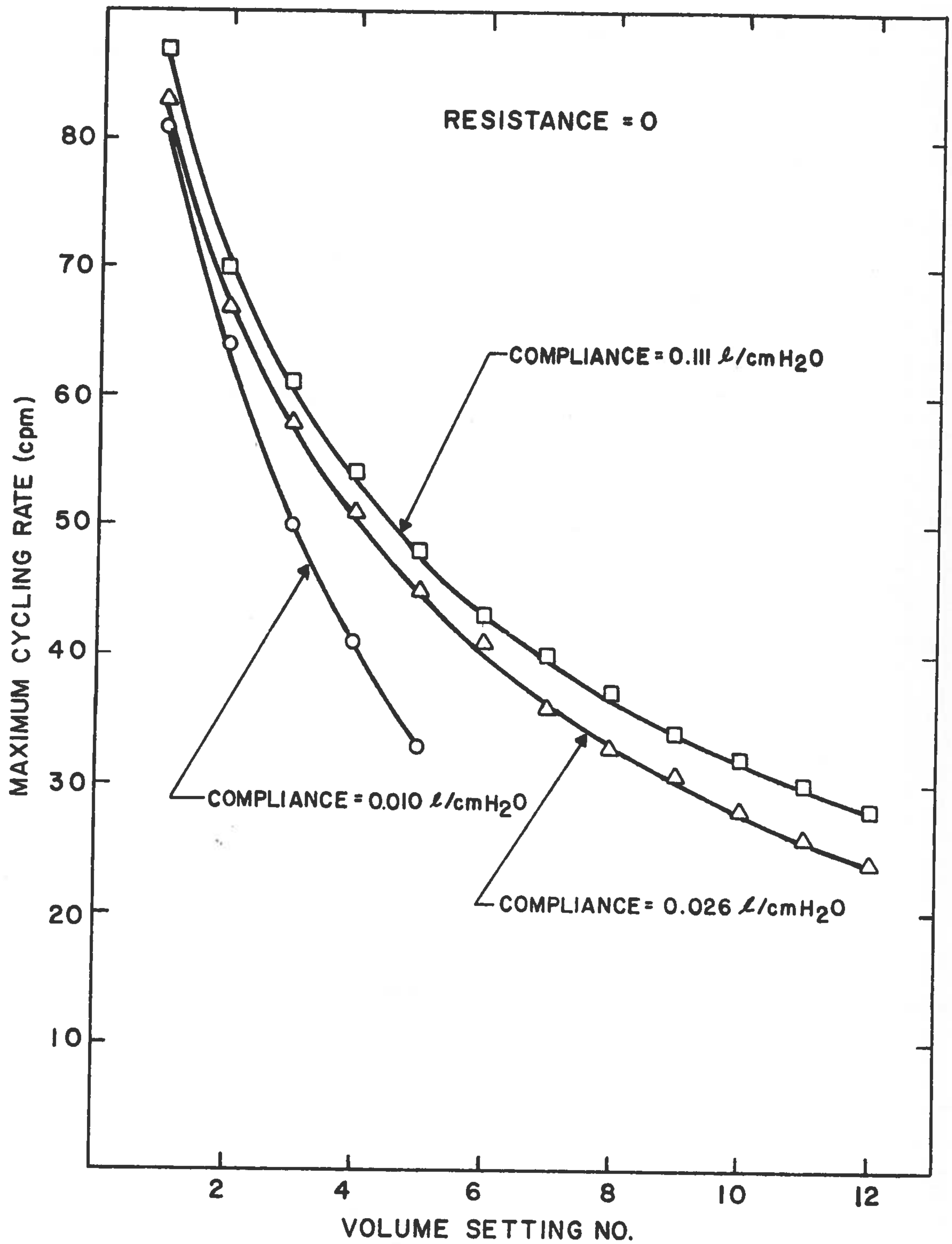

Figure 9. Effect of compliance on cycling rate.

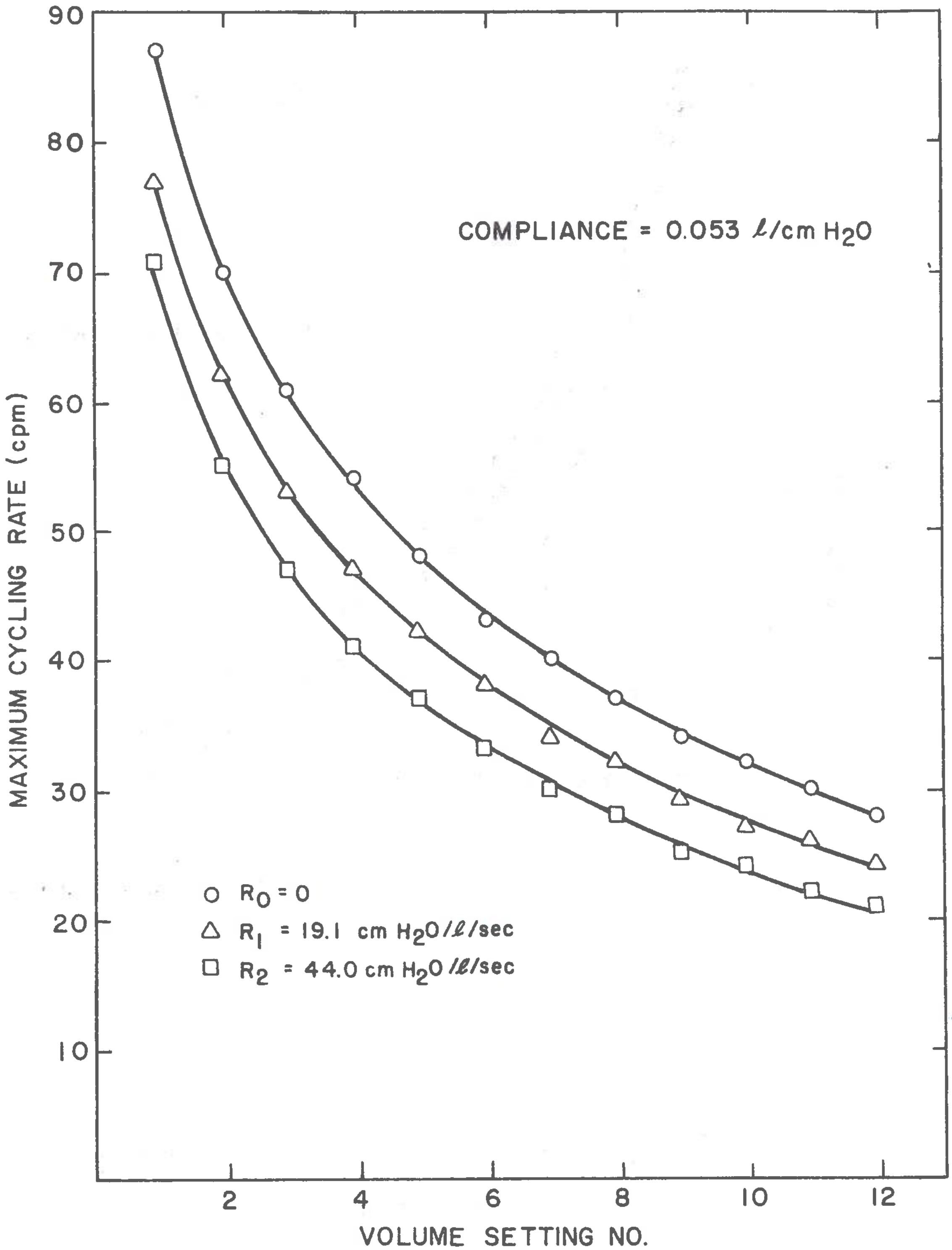

Figure 10. Effect of airway resistance on cycling rate.

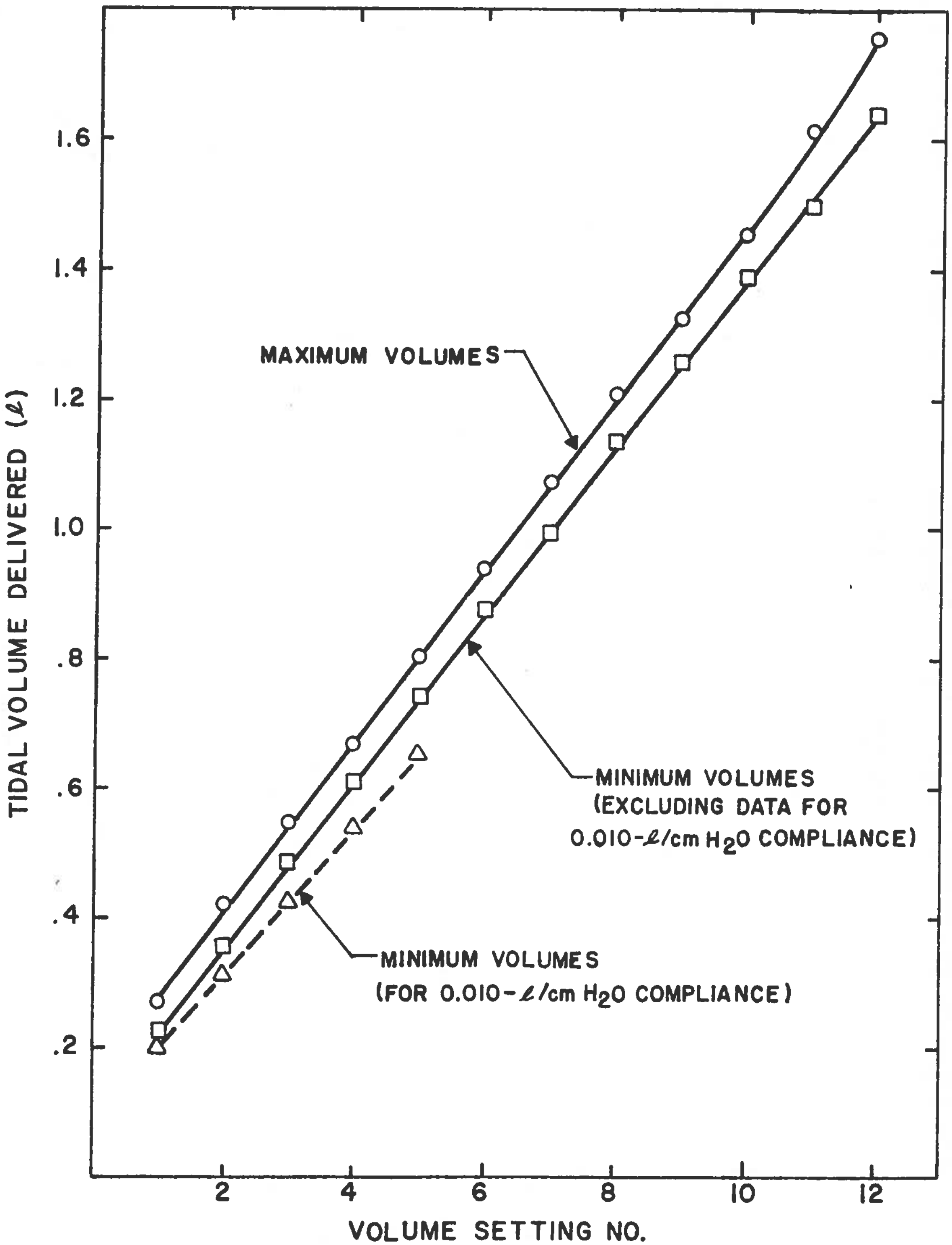

Figure 11. Delivered tidal volumes.

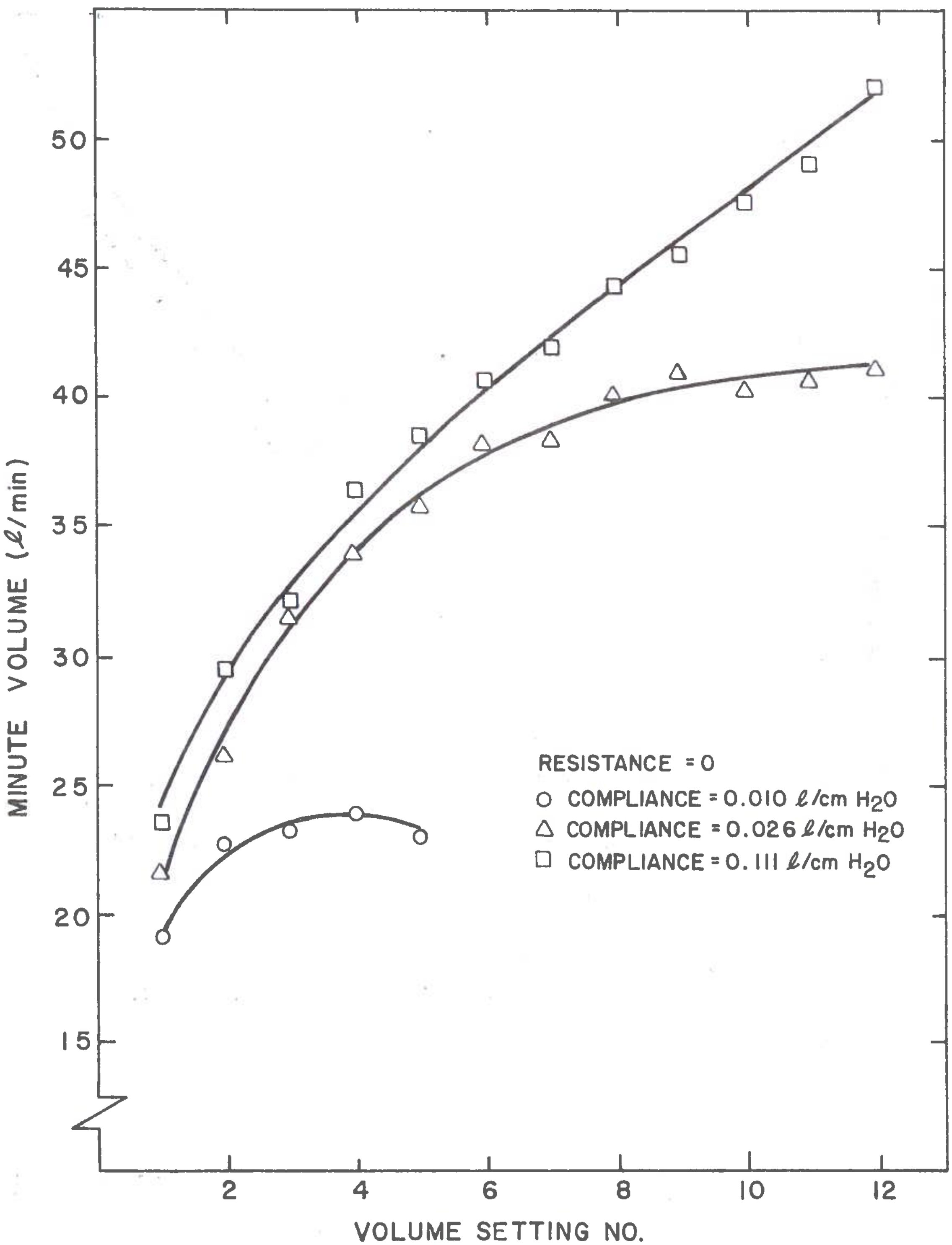

Figure 12. Effect of compliance on minute volume.

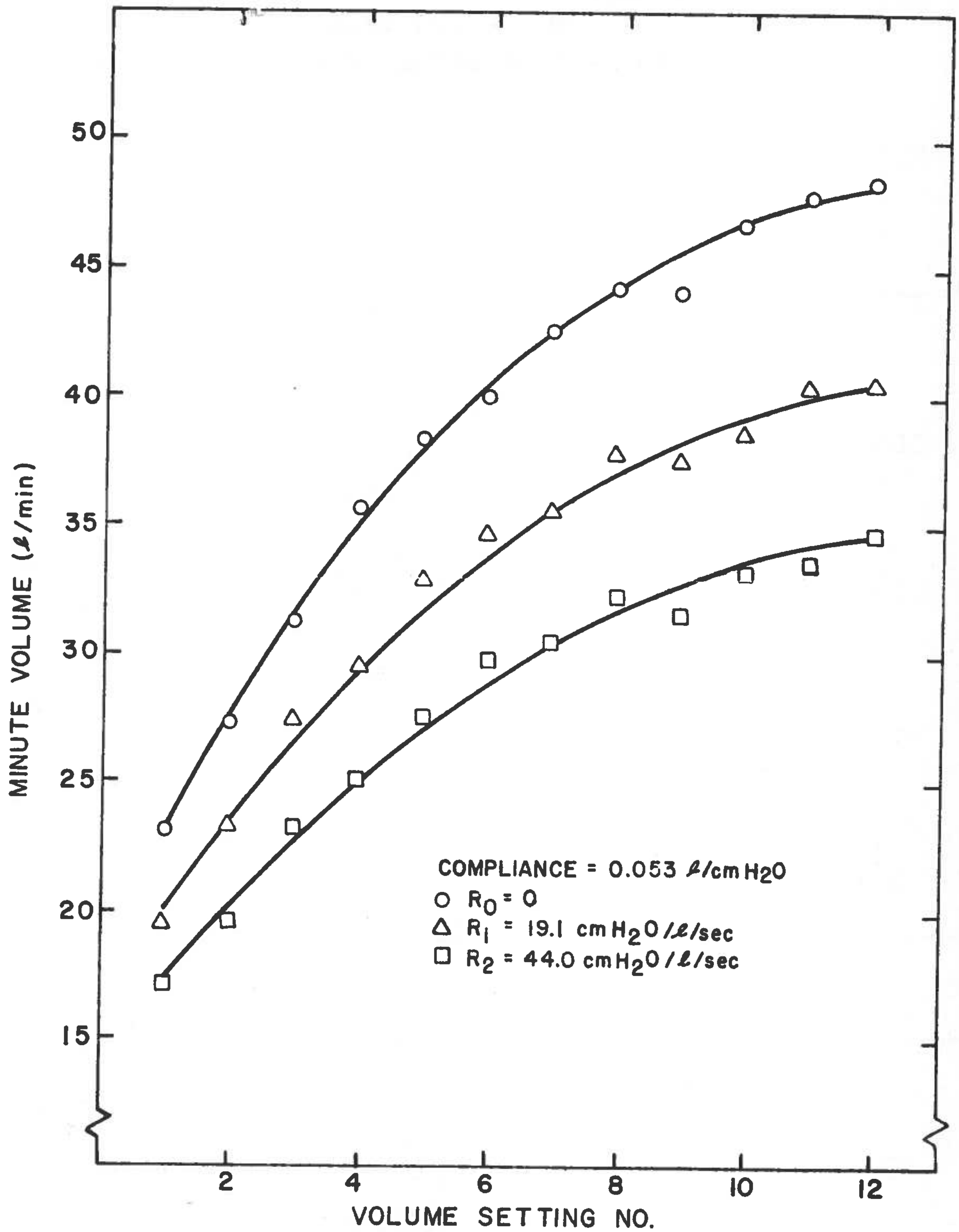

Figure 13. Effect of airway resistance on minute volume.

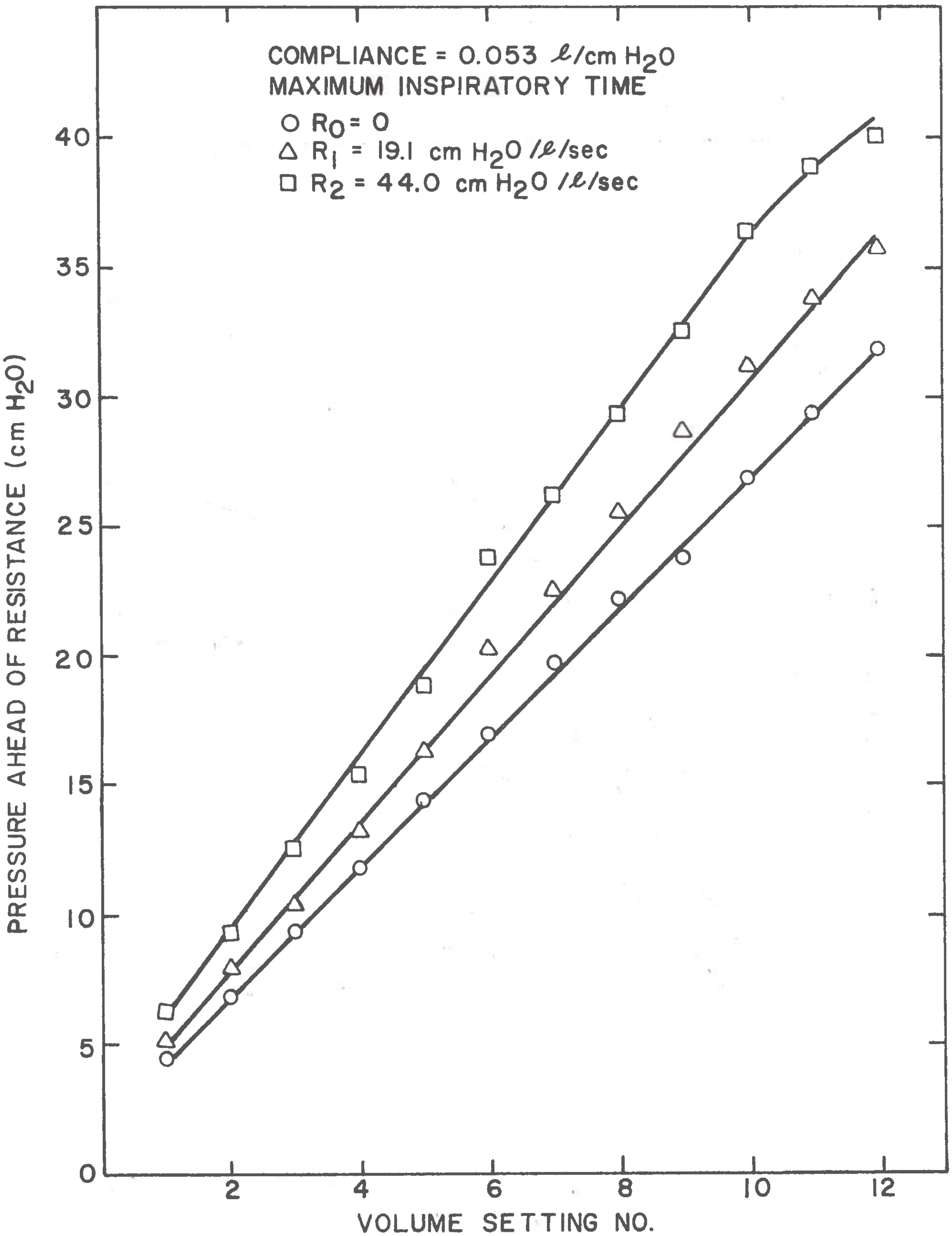

Figure 14. Pressures ahead of airway resistance (maximum inspiratory time).

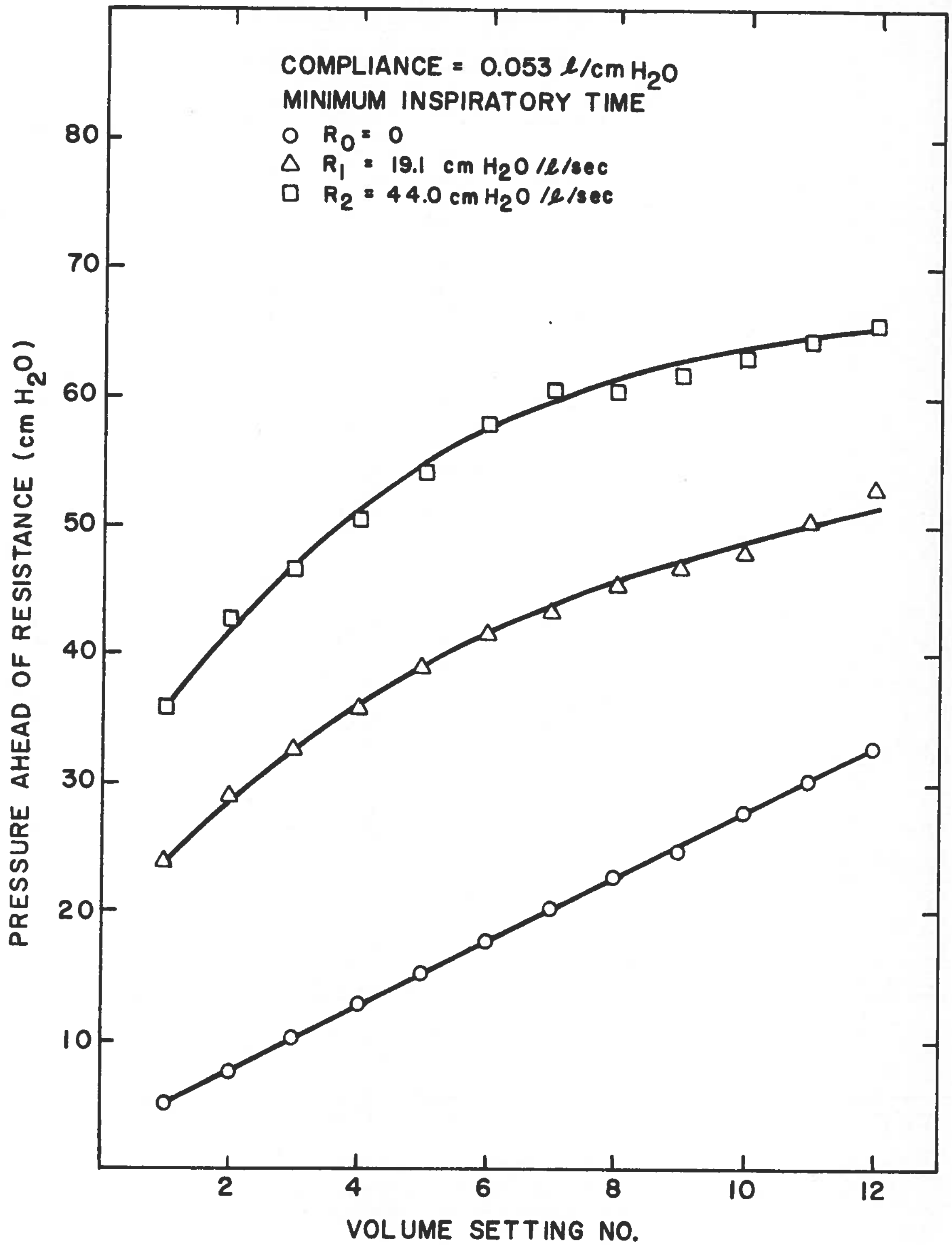

Figure 15. Pressures ahead of airway resistance (minimum inspiratory time).

Appendix A. Inspiratory Times

C	V	$(t_o)_{max}$	$(t_o)_{min}$	$(t_1)_{max}$	$(t_1)_{min}$	$(t_2)_{max}$	$(t_2)_{min}$
0.010	1	0.78	0.25	1.08	0.33	1.00	0.40
	2	1.08	0.36	1.24	0.50	1.32	0.58
	3	1.56	0.56	1.54	0.66	1.52	0.75
	4	1.76	0.78	1.80	0.88	1.82	0.98
	5	1.80	1.06	1.84	1.10	2.00	1.26
0.026	1	0.80	0.23	1.36	0.31	1.08	0.36
	2	1.02	0.32	1.40	0.42	1.40	0.51
	3	1.12	0.40	1.54	0.55	1.64	0.70
	4	1.12	0.50	1.54	0.66	1.70	0.80
	5	1.28	0.60	1.68	0.78	1.90	0.94
	6	1.42	0.68	1.88	0.90	2.00	1.06
	7	1.48	0.80	1.88	1.04	2.15	1.26
	8	1.58	0.90	1.88	1.18	2.25	1.40
	9	1.70	1.02	2.00	1.34	2.30	1.52
	10	1.86	1.16	2.20	1.48	2.40	1.68
	11	2.00	1.30	2.35	1.60	2.60	1.90
	12	2.30	1.44	2.75	1.80	3.00	2.00
0.053	1	0.75	0.20	0.90	0.29	1.16	0.36
	2	0.90	0.28	1.18	0.38	1.40	0.52
	3	1.08	0.36	1.44	0.50	1.80	0.64
	4	1.16	0.44	1.62	0.60	1.92	0.78
	5	1.26	0.52	1.72	0.70	2.05	0.88
	6	1.28	0.60	1.64	0.80	2.10	1.00
	7	1.34	0.66	1.76	0.90	2.20	1.12
	8	1.40	0.72	1.84	1.00	2.30	1.28
	9	1.50	0.80	1.92	1.10	2.40	1.40
	10	1.58	0.88	2.00	1.20	2.50	1.50
	11	1.68	0.96	2.10	1.28	2.60	1.64
	12	1.80	1.04	2.30	1.44	2.80	1.80
0.111	1	0.70	0.20	0.84	0.30	1.20	0.37
	2	1.00	0.28	1.20	0.40	1.44	0.48
	3	1.10	0.35	1.52	0.50	1.80	0.62
	4	1.20	0.42	1.80	0.58	2.10	0.75
	5	1.36	0.50	2.00	0.70	2.45	0.84
	6	1.42	0.55	2.10	0.80	2.70	0.96
	7	1.54	0.62	2.20	0.90	2.95	1.08
	8	1.60	0.70	2.30	1.00	2.85	1.20
	9	1.70	0.76	2.50	1.08	3.20	1.30
	10	1.76	0.82	2.60	1.12	3.30	1.40
	11	2.00	0.88	2.85	1.20	3.70	1.56
	12	2.10	0.94	2.90	1.32	3.90	1.64

C = compliance, ℓ/cm H_2O
V = volume setting number
t_o = inspiratory times for R_o, sec
t_1 = inspiratory times for R_1, sec
t_2 = inspiratory times for R_2, sec

Appendix B. Maximum Cycling Rates

C	V	f_o	f_1	f_2
0.010	1	81	73	67
	2	64	56	52
	3	50	46	43
	4	41	39	36
	5	33	33	30
0.026	1	83	75	71
	2	67	60	55
	3	58	51	45
	4	51	45	41
	5	45	40	36
	6	41	35	32
	7	36	32	28
	8	33	29	26
	9	31	26	24
	10	28	24	22
	11	26	23	20
	12	24	21	19
0.053	1	87	77	71
	2	70	62	55
	3	61	53	47
	4	54	47	41
	5	48	42	37
	6	43	38	33
	7	40	34	30
	8	37	32	28
	9	34	29	25
	10	32	27	24
	11	30	26	22
	12	28	24	21
0.111	1	87	76	70
	2	70	61	57
	3	61	53	48
	4	55	48	42
	5	48	42	38
	6	44	38	34
	7	41	34	31
	8	38	32	29
	9	35	30	27
	10	33	28	25
	11	31	27	23
	12	30	25	22

C = compliance, ℓ/cm H_2O
V = volume setting number
f_o = cycling rates for R_o, cpm
f_1 = cycling rates for R_1, cpm
f_2 = cycling rates for R_2, cpm

Appendix C. Delivered Tidal Volumes

Table C-1. Volumes for Maximum Inspiratory Times

C	V	ΔV_o	ΔV_1	ΔV_2
0.010	1	215	210	205
	2	330	320	310
	3	445	430	425
	4	550	535	540
	5	665	655	665
0.026	1	240	240	225
	2	375	375	355
	3	515	505	495
	4	635	635	615
	5	760	760	760
	6	910	880	880
	7	1040	1025	1025
	8	1175	1175	1155
	9	1310	1275	1275
	10	1405	1405	1405
	11	1540	1540	1500
	12	1670	1640	1640
0.053	1	240	240	240
	2	365	370	365
	3	495	495	495
	4	625	625	625
	5	765	765	765
	6	895	880	895
	7	1040	1030	1030
	8	1175	1160	1145
	9	1255	1255	1255
	10	1420	1420	1390
	11	1550	1550	1520
	12	1685	1650	1650
0.111	1	240	250	240
	2	385	385	375
	3	495	505	495
	4	635	635	635
	5	765	765	755
	6	900	900	890
	7	1020	1020	1020
	8	1165	1165	1135
	9	1300	1300	1265
	10	1440	1440	1410
	11	1585	1540	1510
	12	1730	1685	1650

C = compliance, ℓ/cm H_2O
V = volume setting number
ΔV_o = delivered volume for R_o, mℓ (rounded to nearest 5 mℓ)
ΔV_1 = delivered volume for R_1, mℓ (rounded to nearest 5 mℓ)
ΔV_2 = delivered volume for R_2, mℓ (rounded to nearest 5 mℓ)

Table C-2. Volumes for Minimum Inspiratory Times

C	V	ΔV_o	ΔV_1	ΔV_2
0.010	1	235	230	210
	2	355	345	325
	3	465	465	440
	4	580	565	565
	5	690	680	665
0.026	1	260	250	235
	2	390	390	355
	3	545	520	495
	4	665	650	615
	5	795	780	760
	6	930	910	895
	7	1060	1060	1025
	8	1210	1210	1155
	9	1320	1310	1275
	10	1435	1405	1405
	11	1570	1540	1500
	12	1705	1670	1670
0.053	1	265	250	240
	2	390	375	355
	3	530	515	495
	4	660	625	610
	5	795	780	740
	6	925	895	895
	7	1060	1040	1010
	8	1190	1175	1145
	9	1290	1290	1255
	10	1455	1420	1390
	11	1590	1550	1520
	12	1720	1685	1650
0.111	1	270	255	230
	2	420	390	370
	3	525	505	485
	4	660	635	615
	5	800	765	740
	6	920	900	875
	7	1020	1020	990
	8	1165	1165	1130
	9	1300	1300	1265
	10	1440	1440	1410
	11	1585	1540	1510
	12	1730	1685	1650

C = compliance, ℓ/cm H_2O
V = volume setting number
ΔV_o = delivered volume for R_o, mℓ (rounded to nearest 5 mℓ)
ΔV_1 = delivered volume for R_1, mℓ (rounded to nearest 5 mℓ)
ΔV_2 = delivered volume for R_2, mℓ (rounded to nearest 5 mℓ)

Appendix D. Maximum Minute Volumes

C	V	Q_o	Q_1	Q_2
0.010	1	19.0	16.8	14.1
	2	22.7	19.3	16.9
	3	23.2	21.4	18.9
	4	23.8	22.0	20.3
	5	22.8	22.4	20.0
0.026	1	21.6	18.7	16.7
	2	26.1	23.4	19.5
	3	31.6	26.5	22.3
	4	33.9	29.2	25.2
	5	35.8	31.2	27.3
	6	38.1	31.8	28.6
	7	38.2	34.0	28.7
	8	40.0	35.1	30.0
	9	41.0	34.0	30.6
	10	40.2	33.8	31.0
	11	40.8	35.4	30.0
	12	41.0	35.1	31.7
0.053	1	23.0	19.3	17.0
	2	27.2	23.2	19.5
	3	32.3	27.3	23.2
	4	35.6	29.4	25.0
	5	38.2	32.8	27.4
	6	39.8	34.0	29.6
	7	42.4	35.4	30.3
	8	44.0	37.6	32.1
	9	43.8	37.4	31.4
	10	46.5	38.4	33.3
	11	47.7	40.3	33.4
	12	48.2	40.3	34.6
0.111	1	23.5	19.4	16.1
	2	29.4	23.8	21.0
	3	32.0	26.8	23.2
	4	36.3	30.4	25.8
	5	38.4	32.1	28.1
	6	40.5	34.2	29.8
	7	41.8	34.7	30.7
	8	44.2	37.3	32.9
	9	45.5	39.0	34.2
	10	47.5	40.3	35.2
	11	49.0	41.5	34.7
	12	52.0	42.1	36.3

C = compliance, ℓ/cm H_2O
V = volume setting number
Q_o = minute volume for R_o, ℓ/min
Q_1 = minute volume for R_1, ℓ/min
Q_2 = minute volume for R_2, ℓ/min

Appendix E. Pressures Ahead of Resistance

Table E-1. Pressures for Maximum Inspiratory Times

C	V	P_o	P_1	P_2
0.010	1	21.3	21.9	21.3
	2	33.1	32.5	32.5
	3	44.5	43.8	43.8
	4	55.2	54.0	55.2
	5	66.7	66.7	66.7
0.026	1	9.3	9.3	10.0
	2	14.4	15.0	15.0
	3	19.7	20.0	21.0
	4	24.4	25.6	26.8
	5	29.3	30.6	32.5
	6	35.0	35.7	36.8
	7	40.0	41.3	43.8
	8	45.2	46.5	50.3
	9	50.3	51.5	54.0
	10	54.0	55.2	59.1
	11	59.1	60.4	63.0
	12	64.2	64.2	65.5
0.053	1	4.5	5.1	6.2
	2	6.85	7.95	9.3
	3	9.3	10.3	12.5
	4	11.8	13.1	15.3
	5	14.4	16.3	18.8
	6	16.9	20.3	23.7
	7	19.7	22.5	26.2
	8	22.2	25.6	29.3
	9	23.7	28.7	32.5
	10	26.8	31.2	36.3
	11	29.3	33.8	38.8
	12	31.8	35.7	40.0
0.111	1	2.2	4.35	6.0
	2	3.5	6.2	7.5
	3	4.5	7.5	8.5
	4	5.75	8.7	10.6
	5	6.95	10.0	11.2
	6	8.2	10.9	13.1
	7	9.3	12.5	13.7
	8	10.6	14.0	16.0
	9	11.8	15.7	17.8
	10	13.1	16.9	20.0
	11	14.4	17.5	20.3
	12	15.7	19.4	22.5

C = compliance, ℓ/cm H_2O
V = volume setting number
P_o = peak pressure for R_o, cm H_2O
P_1 = peak pressure ahead of R_1, cm H_2O
P_2 = peak pressure ahead of R_2, cm H_2O

Table E-2. Pressures for Minimum Inspiratory Times

C	V	P_o	P_1	P_2
0.010	1	23.7	33.8	38.2
	2	35.7	43.8	49.0
	3	46.5	51.5	57.8
	4	57.8	61.7	65.5
	5	69.2	71.8	73.0
0.026	1	10.0	27.5	37.5
	2	15.0	33.8	44.4
	3	21.0	38.8	50.3
	4	25.6	43.2	55.2
	5	30.6	47.8	57.8
	6	35.7	51.5	61.7
	7	40.7	54.0	65.5
	8	46.5	57.8	68.0
	9	50.9	61.7	70.5
	10	55.2	64.2	73.0
	11	60.4	68.0	74.3
	12	65.5	70.5	75.5
0.053	1	5.0	23.7	35.7
	2	7.35	28.7	42.5
	3	10.0	32.5	46.5
	4	12.5	35.7	50.3
	5	15.0	38.8	54.0
	6	17.5	41.3	57.8
	7	20.0	43.2	60.4
	8	22.5	45.2	60.4
	9	24.4	46.5	61.7
	10	27.5	47.8	63.0
	11	30.0	50.3	64.2
	12	32.5	52.7	65.5
0.111	1	2.45	23.1	34.4
	2	3.8	28.1	40.7
	3	4.75	30.6	45.2
	4	6.0	33.1	49.0
	5	7.25	35.7	51.5
	6	8.35	37.5	54.0
	7	9.3	39.4	55.2
	8	10.6	41.3	56.5
	9	11.8	42.5	57.8
	10	13.1	43.2	59.1
	11	14.4	44.4	60.4
	12	15.7	45.2	61.7

C = compliance, ℓ/cm H_2O
V = volume setting number
P_o = peak pressure for R_o, cm H_2O
P_1 = peak pressure ahead of R_1, cm H_2O
P_2 = peak pressure ahead of R_2, cm H_2O

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13. ABSTRACT

The Army volume-cycled respirator, which has pressure-cycling capabilities, can assist or control the ventilation of patients. The Model 3 respirator was designed to reduce the internal compliance that caused undesirable performance in the Model 2 unit. Engineering tests using simulated lung compliances and airway resistances show that internal compliance has been reduced from about 0.010 ℓ/cm H_2O in Model 2 to about 0.002 ℓ/cm H_2O in Model 3. Consequently, the variation in delivered tidal volumes due to changes in simulated patient compliance and resistance is much less in Model 3 than in earlier models.

The complete engineering performance of the Model 3 respirator, including inspiratory times, expiratory times, cycling rates, delivered tidal volumes, minute volumes, and mask pressures, are presented. Generally the results show that this respirator has a wide range of performance and is capable of giving adequate ventilation for all test conditions studies.

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