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Comparison of RespirTech PRO and Self-Inflating Bag-Valve Resuscitators During Simulated CPR Chest Compression

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ABSTRACT

BACKGROUND: The cardiopulmonary resuscitation (CPR) guidelines and American Society for Testing and Materials warn against the use of automatic pulmonary resuscitators during CPR closed chest compression because the compression process may interfere with lung ventilation and airway resistance may prevent adequate ventilation. However, appropriately designed pressure-cycled, pressure-controlled (rather than pressure-cycled, time-controlled) mechanical ventilators should be able to automatically respond to pulmonary pressure changes to provide air or oxygen to the lung at high flow rate upon demand and alert the rescuer of ventilatory problems. This evaluation was conducted to investigate ventilatory factors associated with the use of either the portable RespirTech PRO™ (RTP) gas-powered automatic resuscitator or a typical manually operated self-inflating bag-valve resuscitator. METHODS: Thirty tests, 17 with the RTP and 13 with the bag resuscitator, were conducted using the resuscitator connected to a commercial test lung modified for automatic simulated chest-compression following standard compression rates as timed with an electronic metronome. The test system was designed to be totally mechanical to avoid operator effects. RESULTS: Both resuscitators provided appropriate ventilation without excessive lung pressures following the chosen 5:1 compression-ventilation ratio. Overall, the RTP (at 25 L/min) and bag-valve resuscitator minute ventilation values were about the same with means of 6.3±0.5 SE liters and 6.2±0.6 SE liters, respectively.The RTP automatically responded to pulmonary pressure variations, rapidly delivering short breaths between compressions and a full inhalation during the pause without serious pressure extremes.The highest observed intrapulmonary pressures (>80 cm H_2O) occurred with bag-valve resuscitator operated during uninterrupted ("seamless") chest compressions without inhalation synchronization. DISCUSSION: Both devices worked well following the standard protocol for CPR. Because the RTP inhalation-exhalation cycling is visually and audibly obvious, indications of possible airway resistance or low tidal volume are readily observed by the rescuer. CONCLUSIONS: The RTP may be useful as an automatic resuscitator during CPR. Revision of CPR guidelines and ASTM 920-93 for use of pressure-controlled resuscitators should be considered.

INTRODUCTION

Cardiopulmonary resuscitation (CPR) and emergency cardiac care (ECC) are important life-saving procedures.[1] Adjunctive equipment for oxygenation, ventilation, and airway control includes manually-operated self-inflating bag-valve units and pressure cycled automatic mechanical ventilators and resuscitators.[1] During these procedures closed-chest compression may interrupt or interfere with pulmonary ventilation. Intrathoracic pressures may vary depending upon the pulmonary ventilation procedures and the use of adjunctive ventilatory equipment. The flow from gas-powered resuscitators is pressure sensitive and may cease prematurely because of high airway resistance "without alerting the rescuer."[1] Because of these factors and the published guidelines,[1] the American Society for Testing and Materials (Philadelphia, PA) has provided a "Standard Specification for Minimum Performance and Safety Requirements for Resuscitators Intended for Use With Humans" (ASTM Designation 920-93).[2] Specifically paragraph A3.1.31(11.1.1) provides, "*Manufacturer's Warning* - These resuscitators are unacceptable for use during closed chest cardiopulmonary resuscitation because the increase intrathoracic pressure caused during chest compression causes the resuscitator to cycle from the inspiratory mode to the expiratory mode prior to adequate ventilation of the lungs."[2]

Although ASTM provides a prudent general warning for the typical pressure-cycled, time-controlled mechanical ventilators which could malfunction during chest compression, properly designed pressure-cycled, pressure-controlled automatic mechanical ventilators should be able to responsively operate without interfering with adequate ventilation and without the risk of barotrauma during closed chest resuscitation. The portable RespirTech PRO™ (VORTRAN Medical Technology 1, Sacramento, CA) is a pressure-controlled automatic mechanical ventilator that responds to both inspiratory and expiratory pressure and is not time-controlled. This evaluation was designed to investigate the intrapulmonary pressure and ventilatory factors associated with the use of the RespirTech PRO ventilator in combination with simulated chest compression utilizing a representative CPR protocol, a commercial mechanical test lung, and a fully automated mechanical testing system. Comparison tests were also performed utilizing a typical single patient manually-operated bag-valve resuscitator.

The results of this evaluation indicate that the simultaneous use of the RespirTech PRO

during manual chest compression tends automatically to facilitate pulmonary ventilation rather than interfere with it, and with only a modest increase in intrapulmonary pressure during compressions. The manual bag-valve resuscitator also provided satisfactory pulmonary ventilation using a standard CPR protocol, but requires careful synchronization with chest compression pauses.

DESCRIPTION OF DEVICES

The RespirTech PRO (RTP) is an automatic disposable gas-powered resuscitator intended to provide short term ventilatory support to patients while being monitored by a clinician. The RTP provides constant-flow pressure-cycled, pressure-controlled ventilatory support for use by trained personnel who continuously monitor the patient. During inhalation, exhalation will not start until peak pressure is reached. During exhalation, inhalation will not begin until pressure drops to the positive end-exhalation pressure (PEEP). This unique feature among ventilators allows it to operate effectively during CPR. The RTP is shown on a simulated patient model in Figure 1.

The RTP runs on a continuous fixed flow rate of gas (inspiratory flow) of up to 40 L/min. When connected to a 50 PSIG high flow source, the RTP will automatically deliver 40 L/min (667 mL/second). Peak pressure may be adjusted from between 20 and 50 cm H_2O and PEEP is typically $1/10^{th}$ of the peak inspiratory pressure (PIP). This device meets ASTM requirements and includes an inspiratory pressure relief valve that opens automatically at approximately 60 cm H_2O and has a distinctive and easily recognized sound. An optional pressure gage (manometer) allows visualization of airway pressure during use. Also, the audible signal of the inhalation-exhalation breathing cycle allows the rescuer to qualitatively monitor the breathing rate and associated inspiratory tidal volume as an indication of high airway resistance or poor lung compliance.

Manually-operated bag-valve resuscitators are the most commonly used devices for emergency short-term ventilator support. They are typically disposable and are used extensively in the pre-hospital and inter-hospital markets. A trained operator is important for delivery of sufficient tidal volumes at appropriate respiratory rates and proper synchronization with chest compressions pauses. For comparison, parallel tests were conducted with a typical commercial single patient manually-operated bag-valve resuscitator (Ambu SPUR, Ambu Inc., Linthicum,

MD).

EVALUATION METHODS

An integrated mechanical-electrical testing system was designed and constructed using a commercial mechanical test lung (SMS, Harlow Essex, England) set up to simulate a human patient under CPR conditions. This testing system was designed to minimize operator influences during the tests. All data were collected automatically using a real-time computer-based data acquisition system. Figure 2 shows a schematic of the test system in use with the RTP connected to the test lung via a flow rate sensor (Hamilton Medical, Reno NV). Figure 3 shows the same system modified for use with the manual bag-valve resuscitator in place of the RTP. The detailed specifications of the mechanical and electrical components in these test systems are summarized in the Appendix.

The simulated chest compressions were performed automatically using a pneumatic cylinder-operated piston. Compressions were designed from a neutral lung position to cause the exhalation of about 150 mL of air, which is about equivalent to the adult respiratory dead space. The bag-valve resuscitator was operated at a reservoir flow rate of 10 L/min for all tests and tidal volumes of about 0.8 L were automatically dispensed using a pneumatic piston assembly. The RTP was set for a maximum inspiratory flow rate of either 25 L/min or 20 L/min.

In both systems the two-rescuer 5:1 compressions-inhalation ratio protocol was used with the compression rate timed with an electronic metronome and manually activated at a rate of 80 compressions per minute, followed by a distinct pause for one inhalation, the period of which (2¼ s) was dictated by the single inhalation delivery rate of the RTP set to a flow rate of 25 L/min.[1] Various physiological conditions were simulated with the test lung utilizing three settings for airway resistance (20, 50, and 200 cm H_2O/Ls^{-1}) and two setting for lung compliance (0.02 and 0.05 L/cm-H_2O).

In addition, a few of the tests with the manual bag-valve resuscitator were run in asynchronous fashion during uninterrupted compressions at a rate of 80 per minute to simulate potential problems with so-called "seamless" two-rescuer CPR. Because the RTP responds instantaneously to airway pressure changes, no asynchronous tests were possible with it.

The experimental design conditions for the thirty separate tests are summarized in panel A of Table 1 for the RTP and in panel A of Table 2 for the bag resuscitator. The operational

settings of the RTP flow rate (L/min) and the peak inspiratory pressure (PIP, cm H_2O) for the free-running automatic RTP are found in panel A of Table 1. Also found in panel A are the test lung resistance and compliance settings for each test. Likewise, in panel A of Table 2 are found the set flow rate of reservoir for the bag resuscitator and the test lung settings. Also, it is noted whether the test was run under synchronization of the forced breath with the scheduled pause or not. Although the scheduled pause is a component of the protocol for CPR, there is anecdotal information suggesting that the pause is often absent under the pressure of life-threatening heart failure in the patient. Hence, this test was run to evaluate this anomalous "seamless" two-rescuer CPR where a distinct inhalation pause is absent.

It should be noted that the actual inspiratory rate and peak inspiratory pressure are affected by the chest compression procedure in combination with the resuscitator action. The manual bagging technique does not require any settings other than those functionally controlled by the unit, and its application depends in part on the judgement of the user. During the tests, the test lung pressure, proximal airway (simulated trachea) pressure, tidal volume, and respiratory flow rate were automatically recorded as a function of time using a real-time computer-based data collection and processing system. These pressure and volume wave forms were utilized to evaluate successive chest compression strokes and respiratory ventilation. Measurements were made of minute volume (total air inhaled or exhaled) and lung minute ventilation (air entering test lung assuming a nominal adult respiratory dead space of 150 mL).

EVALUATION RESULTS

The results of the 17 tests of the RTP are summarized in panel B of Table 1 providing the respiratory minute volume, the lung minute ventilation, the peak tidal volume, the peak proximal airway (tracheal) pressure during forced inhalation, the peak lung pressure during chest compression, and the fraction of time (%) that the lung pressure exceeded 50 cm H_2O. The results of the 13 tests of the bag resuscitator are summarized in panel B of Table 2 providing the respiratory minute volume, the lung minute ventilation, the peak tidal volume, the peak proximal airway (tracheal) pressure during forced inhalation, the peak lung pressure during chest compression, and the fraction of time (%) that the lung pressure exceeded 50 cm H_2O. Overall, the RTP (at 25 L/min) and synchronized bag-valve minute ventilation values were very similar with means of 6.3±0.5 SE liters and 6.2 ±0.6 SE liters, respectively.

Representative plots of the pressure and volume measurements are shown in Figure 4 for an RTP test, in Figure 5 for a bag test, and in Figure 6 for an asynchronous bag test. These plots and the associated data show that the RTP tended to supply a small breath (barely exceeding the dead space volume) between each compression resulting in higher (but not excessive) lung pressures during compressions than achieved during compressions with the bag resuscitator which was set to supply air only during the scheduled inspiratory pause (contrast panels A and C in Figures 4 and 5). Also, the bag resuscitator produced flow rates approaching 80 L/min during the inhalation pause (panel C, Figure 5) compared to the set (usually 25 L/min) flow rate maintained by the RTP during the inhalation pause (panel C, Figure 4). Likewise, the bag resuscitator produced much higher proximal airway pressures (often over 90 cm H_2O, Table 2 and panel B of Figure 5) than did the RTP whose proximal airway pressure was limited to the preset PIP (usually 25 cm H_2O, Table 1 and panel B of Figure 4). Higher lung pressures were observed with the RTP (Table 1 and panel D of Figure 4) than for the properly synchronized bag resuscitator (Table 2 and panel D of Figure 5), but they rarely exceed 60 cm H_2O and the fraction of time the lung was at pressures exceeding 50 cm H_2O was small (the highest being 6% associated with higher airway resistance, Table 1).

The highest lung pressures in the study (84.1, 88.7, and 90.5 cm H_2O) occurred during asynchronous use of the bag resuscitator (Table 2 and panel D of Figure 6). The greatest variability of minute volume and minute ventilation also occurred under these asynchronous conditions with the bag resuscitator (Table 2).

When elevated airway resistance (or obstruction) was simulated with resistance setting of 200 cm H_2O/Ls^{-1}, the RTP rapidly cycled between inhalation and exhalation modes (Table 1). This rapid cycling was audibly and visually obvious, indicating inadequate tidal volumes.

DISCUSSION

Clearly, normal inhalation is not possible during forced chest compression. Hence, the ventilatory pause that is part of the standard CPR protocols for chest compression provides a window of opportunity for inhalation and lung inflation. The about 2 seconds needed for a full inspiratory breath by the RTP because of the chosen preset inspiratory flow rate is somewhat longer than the usually recommended pause of 1 to 1½ seconds.[1] A full lung inflation in 1 second is readily possible with the bag resuscitators because of the higher inspiratory flow rate and

higher proximal airway pressures. A well trained rescuer, can readily provide adequate ventilation with a bag resuscitator in this short pause time. On the other hand, it is also possible to push air into the lung against the force of the chest compression with the bag resuscitator, while this is not possible with the RTP because it instantaneously responds to elevated pressures, turns off the inspiratory airflow, and enters exhalation mode at pressures above the set PIP. In this study, the highest lung pressures (>80 cm H_2O) occurred during asynchronous use of the bag-valve resuscitator (Table 2). It would appear that the inherent difficulties associated with "seamless" uninterrupted compressions during attempted forced synchronized inhalations with a bag-valve resuscitator would discourage such maneuvers. In the case of the RTP, no asynchronous ventilation can occur because of the instantaneous response of the RTP to airway pressure. But inspiratory pauses are essential with the RTP when the flow rate is set at 25 L/min to provide adequate ventilation.

The fact that the RTP provides some inspiratory flow between compressions is shown by the increases in lung volume, larger minute volume, and somewhat higher lung pressure during compression compared to that observed during use of the bag resuscitator (Tables 1 and 2). The fact that the inter-compression inspiratory flows are small and of the order of the respiratory dead space in these studies, leads to larger differences between minute volume and minute ventilation using the RTP (Table 1) compared to the corresponding values observed during bagging (Table 2) where no breaths are delivered between compressions until the inspiratory pause.

The combination of the PIP setting of the RTP and the force of the compression led to peak compression pressures that were about two times the PIP (Table 1 and Figure 4). These momentary elevated pressures were well within acceptable limits for intrapulmonary pressure (always less than 70 cm H_2O with the RTP PIP set at 25 cm H_2O). Lung pressures greater than 50 cm H_2O occupied less than 6% of the respiratory period with the RTP. On the other hand, lung pressure was minimal during compression with the bagging technique indicating virtually no inspiratory ventilation between compressions.

Various studies have shown that elevated intrathoracic pressures during chest compression facilitates the increase in cardiac blood pressure.[6-7] The fact that the RTP tends to maintain some minimal level of lung volume between compressions may be helpful in elevating the cardiac pressure during chest compression. Since the bag resuscitator is not providing air during compressions, thoracic pressure is minimized.

When elevated airway resistance (or obstruction) was simulated with resistance setting of 200 cm H_2O/Ls^{-1}, the rapid cycling of the RTP was audibly and visually obvious, indicating inadequate tidal volumes. Since inspiratory flow rate is known and constant with the RTP, the tidal volume is simply the inspiratory time multiplied by the known flow rate. When short breaths occur, the rescuer can readily estimate the associated tidal volume and decide whether the minute ventilation is inadequate. A rescuer can respond by increasing the airway pressure setting (PIP) or taking other corrective action.

Ventilatory support is an important aspect of CPR. The effectiveness of that support depends, in part, on the methods utilized. Gervais, et al.[3] and Braman et al.[4] demonstrated the importance of ventilatory methods on blood pCO_2 and pO_2 by comparing manual and mechanical ventilation in patients during transport. Braman et al.[4] also showed the importance of minute volume. Hurst et al.[5] showed that use of a time-cycled IMV Bird transport mechanical ventilator was superior to manual ventilation when used with a critically ill patient based on pCO_2. After manual ventilation all patients showed marked respiratory alkalosis.

During chest compression, full inhalation is prevented so that automatic high flow rate inspiration immediately following compression is desirable to provide for adequate ventilation. Although automatic pressure-controlled mechanical ventilators can serve as effective resuscitators, the National Conference on CPR and ECC[1] and ASTM[2] warnings against the use of mechanical ventilators during CPR chest compression would preclude their use in many critical cases. In principle, pressure-controlled ventilators, such as the RTP which operate based on airway pressure, can respond nearly instantaneously to lung pressure changes during chest compression and should, therefore, not interfere with optimal ventilation and may, in fact, enhance ventilation during CPR. On the other hand, most mechanical ventilators in use are time-cycled. The ECC and ASTM warnings seem most appropriately directed to these time-cycled ventilators since their timing can be seriously disrupted by chest compressions.

The results of this evaluation suggest that there is no apparent contraindication associated with performing CPR closed chest compression while utilizing the RTP as a ventilatory resuscitator. Further, the results suggest that such use would be beneficial to the patient by providing automatic high flow rate inhalation flows immediately after chest compression strokes without manual synchronization.

CONCLUSION

The results of this evaluation indicate that the simultaneous use of the RTP during manual chest compression tends automatically to facilitate pulmonary ventilation rather than interfere with it, and with only a modest increase in intrapulmonary pressure during compression.. On the other hand the manual bag-valve resuscitator requires trained synchronization to avoid markedly increased intrapulmonary pressures caused by asynchronous inhalations and compressions.

These results suggest that there is no apparent contraindication associated with performing CPR closed chest compression while utilizing the RTP as a ventilatory resuscitator. Further, the results suggest that such use would be beneficial. A revision of CPR guidelines and ASTM 920-93 should be considered.

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PRODUCT SOURCES

The single patient manually-operated bag-valve resuscitator used in this evaluation is the Ambu® SPUR Adult Resuscitator (Cat No. 420611000). It is commercially available from Ambu Inc., Linthicum, MD. The list price is $10.

The automatic pressure-controlled resuscitator used in this evaluation is the portable gas-power RespirTech PRO™ (Order No. 2000). It is commercially available from VORTRAN Medical Technology 1, Sacramento, CA. The list price is $29. The accessory manometer is a 5 to 60 cm H_2O pressure gage is an additional $10.

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APPENDIX: Test Setup Component Specifications

RespirTech PRO: VORTRAN Medical Technology 1, Inc., Sacramento, CA.
Part No: 2000 Lot No: 98007

Self-Inflating Bag Resuscitator: AMBU SPUR Adult Resuscitator, Ambu Inc., Linthicum, MD.
Catalog No: 420611000 Lot No: 98313

Test Lung: SMS, Harlow Essex, England.
Model No: MS0015001 Serial No: AC97006S

Flow Sensor: Hamilton Medical, Reno, NV.
Model No: Hamilton Sensor

Pressure Transducers: Microswitch Corporation, Los Angeles, CA.

Channel -1 Range:	0.0833 Volts/cm-H_2O
Channel -2 Range:	0.1666 Volts/cm-H_2O
Channel -3 Range:	0.1666 Volts/cm-H_2O

Data Acquisition Hardware: ComputerBoards, Inc. Mansfield, MA.
Model No: CIO-DAS 1600/16

Data Acquisition Software: Laboratory Technologies Corp, Wilmington, MA.
Version No: 10.02 Serial No: 34761

Air Compressor: Powerex Inc., Harrison, OH
Model No: OL75OP Serial No: E66385T 23649081

Flowmeter: Timeter Group, Allied Health Care Products, Inc., St. Louis, MO.
Model No: 0-75 L/Min

Pressure Regulators: Monnier Inc., Algonac, MI.
Model No: 101-3002-1

Piston Air Cylinder for Lung Simulator: Speedaire, Niles, IL.
Model No: 6W159, operated at 10 L/min flow rate.

Piston Air Cylinder for Bag operation: Humphrey, Kalamazoo, MI.
Model No: KALAMA200, operated at 29 L/min flow rate.

Solenoid Valves to Control Bag's Piston Air Cylinder: Numatics, Highland, MI.
Model No: H003M7H

Solenoid Valves to Control Lung Simulator Piston Air Cylinder: ARO Corp., Bryant, OH.
Model No: Sierra, S5SSMB

Control On / Off Switches: Various manufacturers, Generic switches.

Table 1: Effect of RespirTech PRO (RTP) Resuscitator Test Conditions on Ventilation.

A. RTP AND TEST LUNG SETTINGS					B. RESULTS OF TESTS					
Test ID	Flow (L/min)	PIP (cm H_2O)	Resistance (cm H_2O/Ls^{-1})	Compliance (L/cm-H_2O)	Volume (L/min±SE)	Ventilation (L/min±SE)	Peak Tidal Volume (L)	Peak Proximal Press. (cm H_2O)	Peak Lung Press. (cm H_2O)	Time > 50 cm H_2O (%)
A1	25	25	20	0.05	16.0±0.2	8.5±0.1	0.97	24.3	60.1	4.2
A2	25	25	20	0.05	17.1±0.2	9.6±0.1	1.03	24.1	66.6	3.6
A3	25	25	20	0.05	16.8±0.9	9.3±0.6	1.10	23.8	62.2	2.8
B1	25	20	20	0.05	14.5±0.4	7.0±0.3	0.77	16.7	44.0	0
B2	25	20	20	0.05	15.3±1.2	7.7±0.9	0.84	19.4	51.5	0.3
C1	15	25	20	0.05	11.4±0.2	4.1±0.1	0.68	22.9	66.0	2.5
C2	15	25	20	0.05	12.9±0.3	5.6±0.1	0.80	25.2	64.8	2.5
D1	25	25	50	0.05	12.8±0.5	5.3±0.4	0.72	21.5	59.1	4.2
D2	25	25	50	0.05	13.6±0.5	6.0±0.4	0.80	24.3	62.3	6.0
E1	25	25	200	0.05	nil	nil	nil	21.0	51.6	0.0
F1	25	25	20	0.02	14.5±0.6	7.0±0.5	0.58	21.6	46.4	0
F2	25	25	20	0.02	14.8±0.7	7.3±0.5	0.68	24.0	54.1	0.2
H1	15	25	20	0.02	11.2±0.3	3.8±0.2	0.66	22.7	51.7	0.5
H2	15	25	20	0.02	12.2±0.3	4.8±0.2	0.76	25.7	53.8	1.0
I1	25	25	50	0.02	12.3±0.5	4.8±0.3	0.46	21.6	55.1	1.3
I2	25	25	50	0.02	12.9±0.7	5.4±0.5	0.57	23.5	57.9	3.0
J1	25	25	200	0.02	nil	nil	nil	23.0	32.0	0

Table 2: Effect of Self-inflating Bag-type Resuscitator Test Conditions on Ventilation.

A. FLOW AND TEST LUNG SETTINGS					B. RESULTS OF TESTS					
Test ID	Flow (L/min)	Synchro-nization	Resistance (cm H_2O/Ls^{-1})	Compliance (L/cm-H_2O)	Volume (L/min±SE)	Ventilation (L/min±SE)	Peak Tidal Volume (L)	Peak Proximal Press. (cm H_2O)	Peak Lung Press. (cm H_2O)	Time > 50 cm H_2O (%)
K1	10	YES	20	0.05	7.6±0.1	6.1±0.1	0.73	60.0	38.3	0
K2	10	YES	20	0.05	8.1±0.4	6.7±0.4	0.81	58.9	39.8	0
L1	10	NO	20	0.05	8.6±0.7	6.8±0.5	0.61	93.3	84.1	1.1
L2	10	NO	20	0.05	13.4±1.1	10.3±0.8	0.74	93.3	90.5	3.3
M1	10	YES	50	0.05	6.9±0.2	5.4±0.2	0.64	87.5	43.7	0
M2	10	YES	50	0.05	7.5±0.1	6.0±0.1	0.69	87.5	45.9	0
N1	10	YES	200	0.05	5.4±0.1	3.9±0.1	0.52	>120.	59.1	0.6
O1	10	YES	20	0.02	9.8±0.2	8.3±0.2	0.67	61.4	37.3	0
O2	10	YES	20	0.02	10.9±0.2	9.5±0.2	0.78	61.4	31.7	0
P1	10	NO	20	0.02	12.1±0.8	9.9±0.6	0.74	92.9	88.7	2.7
Q1	10	YES	50	0.02	7.6±0.3	6.1±0.2	0.66	88.5	42.2	0
Q2	10	YES	50	0.02	7.9±0.2	6.4±0.2	0.7	88.5	43.8	0
R1	10	YES	200	0.02	5.4±0.1	3.9±0.1	0.56	>120.	54.0	0.3

FIGURE CAPTIONS

Figure 1: Photograph of the RespirTech PRO (RTP) as it appears in use providing automatic ventilatory support for a patient (*model simulation*).

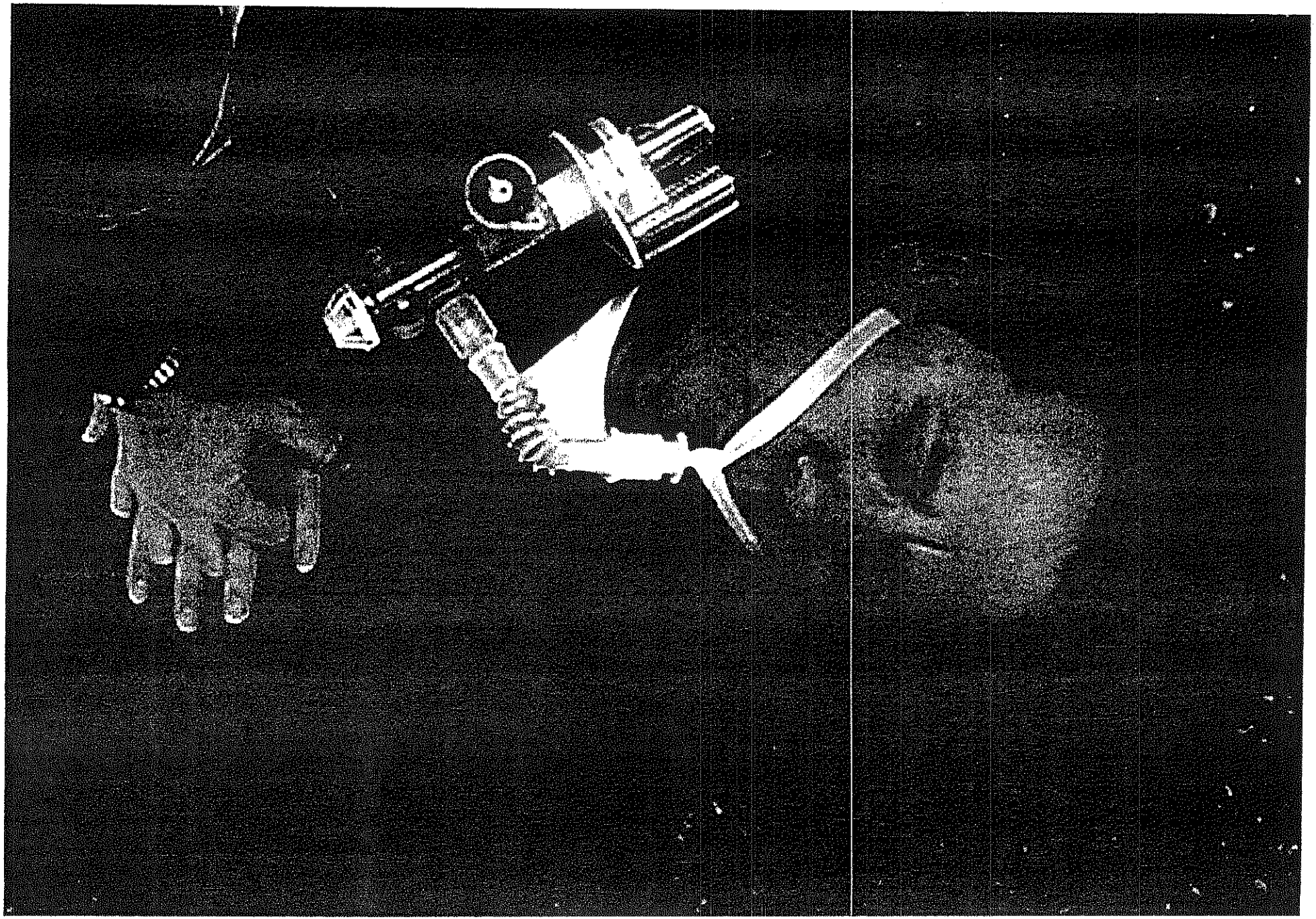
Figure 2: Schematic diagram of the test lung apparatus as used in this research for studies of the RespirTech PRO resuscitator.

Figure 3: Schematic diagram of the test lung apparatus as used in this research for studies of the bag-valve resuscitator.

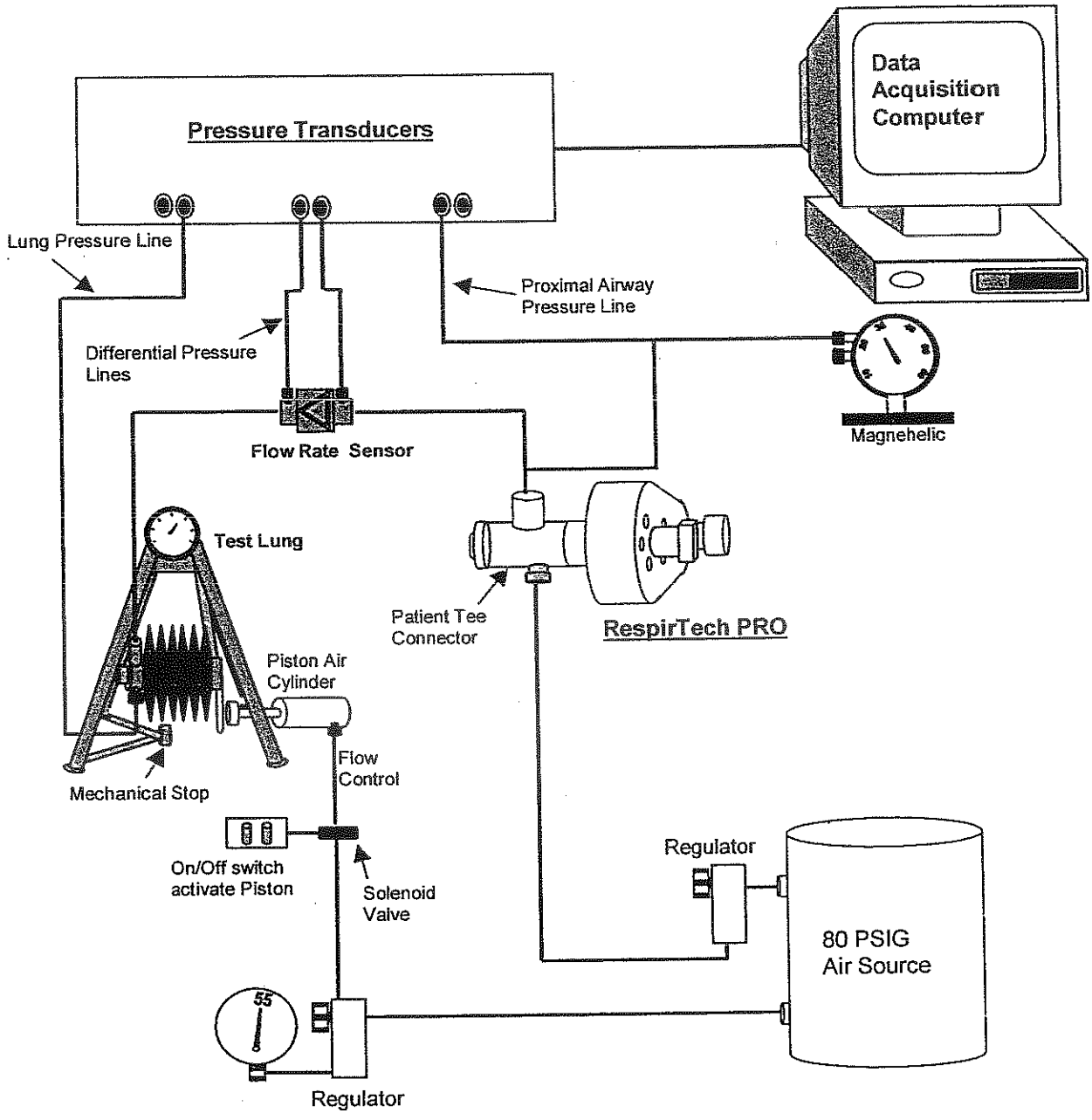
Figure 4: Representative pressure and volume patterns obtained during tests with the RespirTech PRO™ using a 5:1 compression-ventilation ratio with a compression rate of 80 per minute and 2¼ seconds inhalation pause showing [A] lung volume (with respect to approximate end-exhalation baseline), [B] proximal airway pressure, [C] bidirectional airway flow rate, and [D] lung pressure.

Figure 5: Representative pressure and volume patterns obtained during tests with the self-inflating bag-valve resuscitator using a 5:1 compression-ventilation ratio with a compression rate of 80 per minute and 2¼ seconds inhalation pause showing [A] lung volume (with respect to approximate end-exhalation baseline), [B] proximal airway pressure, [C] bidirectional airway flow rate, [D] lung pressure.

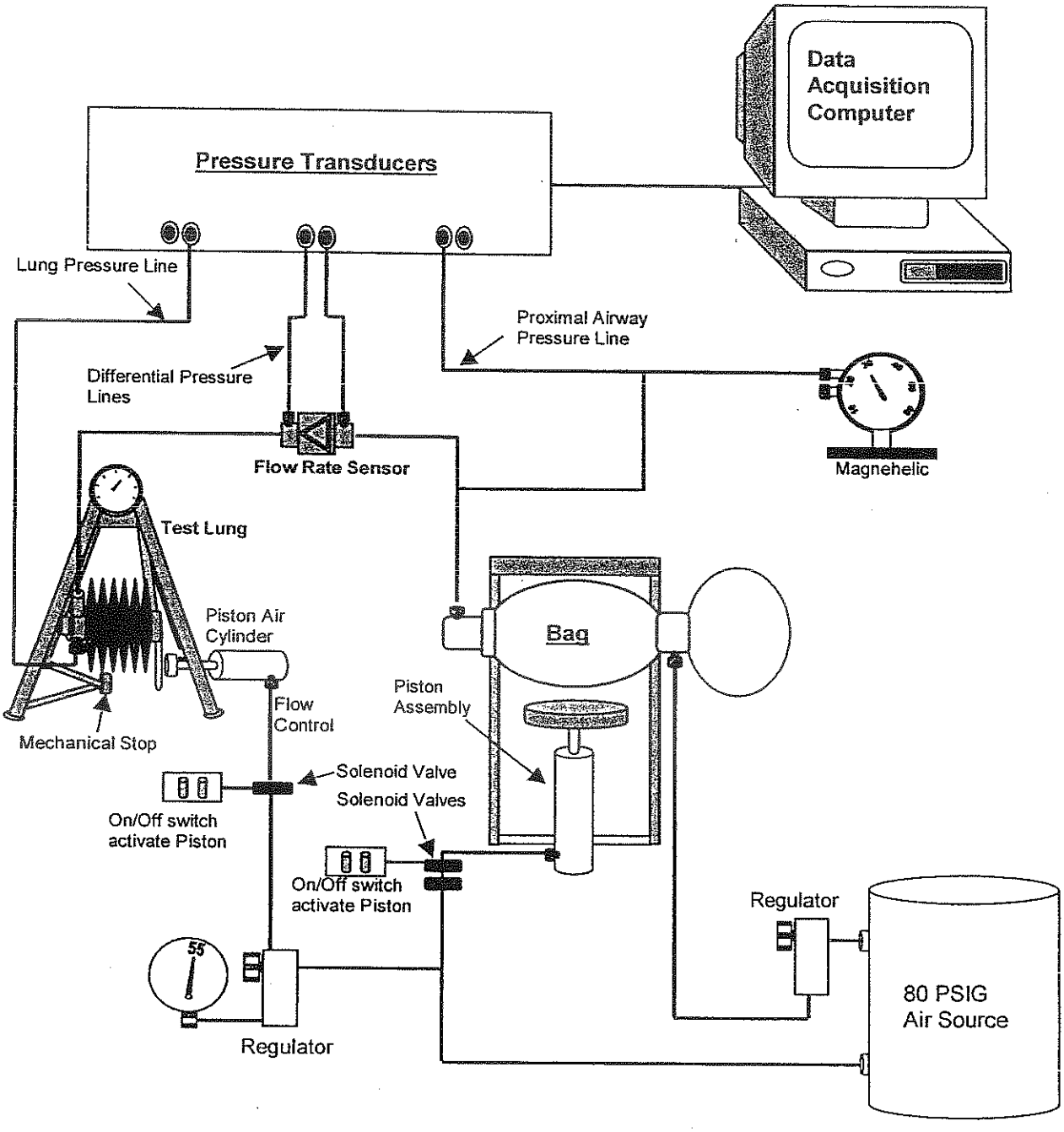
Figure 6: Representative pressure and volume patterns obtained during tests with the self-inflating bag-valve resuscitator using a continuous compression rate of 80 per minute and asynchronous ventilation pulses showing [A] lung volume (with respect to approximate end-exhalation baseline), [B] proximal airway pressure, [C] bidirectional airway flow rate, [D] lung pressure.



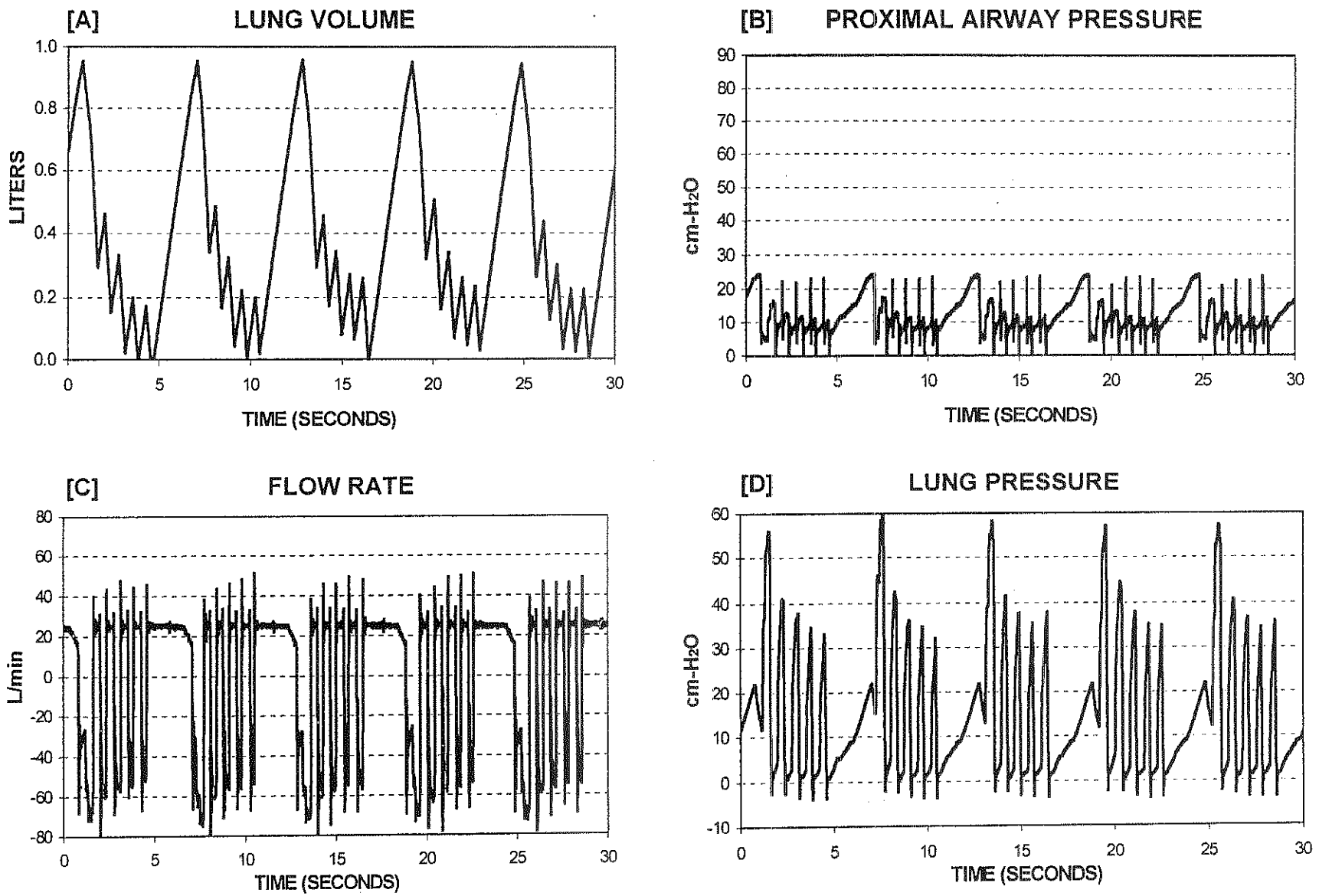
RespirTech PRO and Bag Resuscitator
Figure 1



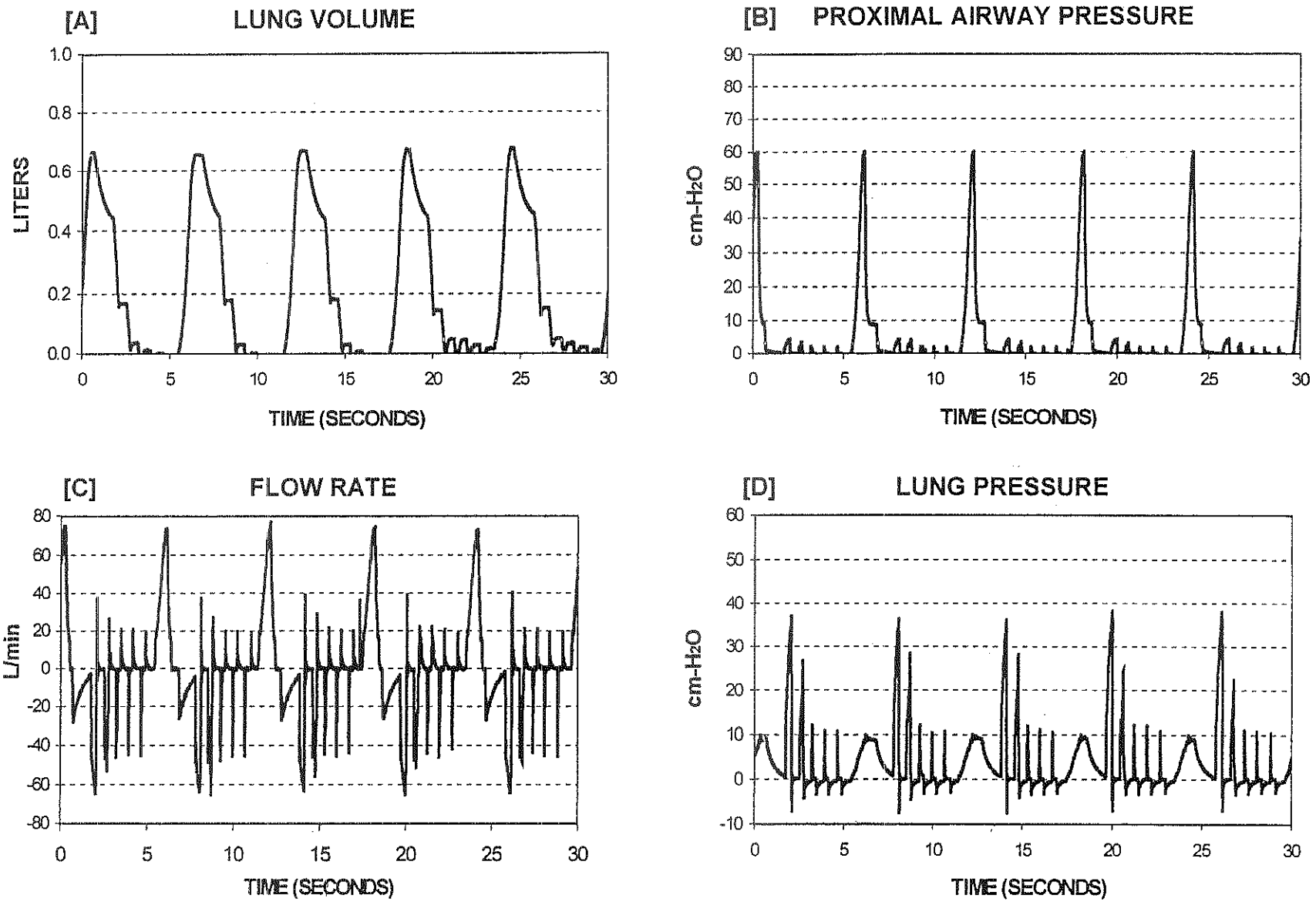
RespirT ʰ PRO and Bag Resuscitator



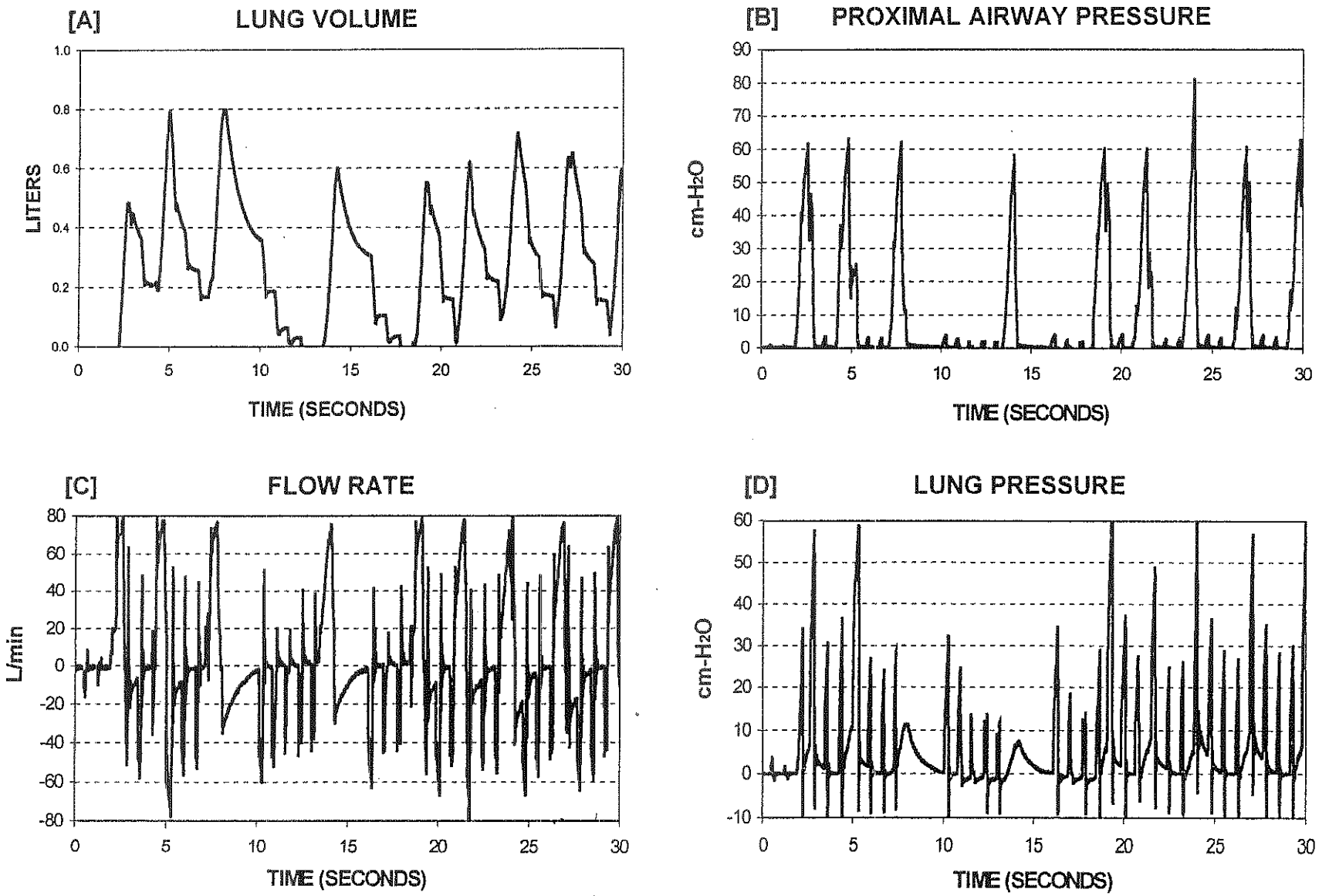
RespirTech PRO and Bag Resuscitator
Figure 3



RespirTech PRO and Bag Resuscitator
Figure



RespirTech PRO and Bag Resuscitator
Figure



RespirTech PRO and Bag Resuscitator
Figure 6