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HUMAN BREATHING PARAMETERS AND COMMERCIAL AUTOMATIC RESPIRATORS

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CONTENTS

ILLUSTRATIONS

ABSTRACT

During periods of inadequate human respiration, artificial ventilation can satisfactorily assume the function of the patient's breathing mechanisms in most situations. Such ventilation can be administered by mouth to mouth techniques, manual methods, or automatic devices. The purpose of this report is to discuss the physiological parameters governing the design of automatic respirators and to review the design of those currently in use.

PART I - PULMONARY PHYSIOLOGY - PHYSICAL PARAMETERS

by Capt. G. Thompson

1.1 INTRODUCTION

The main function of the respiratory passageways is to conduct air to the millions of the pulmonary alveoli. There, the greatly magnified air-blood interface allows for rapid gas transfer. In addition to its primary function of air conduction, the tracheo-broncheal tree also serves to warm, filter, and humidify inspired air so that gas transfer may proceed in the most efficient manner.

Both the process of ventilation and of gas transfer to blood can be accomplished by artificial means. Some of the physiological parameters governing the design of ventilation equipment follow.

1.2 LUNG ANATOMY AND VOLUMES

Due to the left-sided location of the heart, the three lobes of the right lung occupy about 20 percent more volume than the two lobes of the left lung. About 55 percent of the inspired tidal volume is distributed to the right lung. Even in normal lungs, there is unequal distribution and mixing of inspired air. Pulmonary blood flow is also known to vary between the two lungs, and to be affected by changes in the individual's posture. The ventilation- to blood-flow ratio is a basic consideration in determining how effective gas transfer will be. There are numerous pathologic conditions in which either ventilation flow or blood flow is altered.

During an average inspiration, an adult breathing at a rate of 16 times per minute inhales a volume of about 500 cc of air in a single breath. The amount of air inhaled per breath is termed tidal volume. In children, it decreases to normal values of 40 to 100 cc while the breathing rate increases to 30 to 40 times per minute. The product of tidal volume and respiratory rate produces the minute respiratory volume. In a normal adult this averages from 6 to 8 ℓ/min. Minute volume can be increased to as much as 170 ℓ/min by forced breathing. Mechanical ventilation of the lungs rarely requires a minute volume greater than 15 ℓ/min.

Approximately one third of each tidal volume goes to fill elements of the respiratory passageways that have no membranes for gas transfer. This volume is termed dead space.

1.3 INTRAPULMONARY AND INTRAPLEURAL PRESSURES

Normally, the energy required for inspiration is supplied by muscles acting upon the thoracic cage. When these muscles contract, the intrapulmonary pressure decreases, and air is sucked into the lungs. As the muscles relax, the elastic thoracic cage contracts and expiration occurs. The pressure changes caused by muscle contraction are first reflected in the intrapleural space and then in the intrapulmonary regions. Intrapleural pressures normally range from about -2 mm Hg during expiration to -8 mm Hg during inspiration. There is a negative pressure within the intrapleural space at all times. Corresponding pressures in the intrapulmonary regions are +3 mm Hg during expiration and -3 mm Hg during inspiration. A healthy adult can voluntarily force these pressures to about +100 mm Hg during expiration and -80 mm Hg during inspiration.

During normal breathing, the negative inspiratory pressure in the intrapleural space aids venous return to the heart. The great veins emptying into the heart are located in the intrapleural space, although surrounded by the pleura. As intrapleural pressure becomes more negative, the walls of the veins become distended, allowing more blood to pass because of the correspondingly larger cross-sectional areas. In patients being ventilated with mechanical devices, the application of negative pressure to the airway during assisted expiration tends to aid venous return.

1.4 COMPLIANCE

Compliance, the term used to define the elastic properties of the lungs and thorax, is expressed as the volume increase in the lungs resulting from an increase in intra-alveolar pressure. Normal values are 0.22 ℓ/cm H_2O for lungs and thorax combined. The elasticity of the thorax is due to the elastic structures comprising the chest cage. Approximately one-third of the elasticity of the lungs is due to elastic fibres within the lung tissue; the remainder is due to the surface tension of a fluid called surfactant that coats the inner surface of the alveoli. Surfactant is probably lipoprotein and can be extracted for measurements on a surface-tension balance. Under certain conditions, such as occur in Hyaline membrane disease, the surfactant is altered to cause an abnormally high tendency for the alveoli to collapse. Lung compliance is greatly increased in these instances. Likewise compliance of both lungs and thorax will change with any of the numerous pathologic conditions affecting the elasticity of these structures.

1.5 RESISTANCE

In addition to compliance, resistance must be considered in determining the total energy involved in breathing. Two kinds of resistance are present in the breathing process. The first, viscous resistance, is that resulting from the molecular rearrangement within the tissues. Under normal conditions it is of relatively little importance. The second kind of resistance is that resisting the flow of air along the respiratory passageways. This resistance is different for laminar and turbulent flows. While viscous resistance is of relatively little importance under normal conditions, as certain diseases such as asthma progress, the airways become markedly narrowed with increased turbulent flow. Then viscous resistance can account for a significant portion of the total energy of breathing.

Normal values of airway resistance for the adult are in the range of 1 to 2 cm $H_2O/\ell/sec$ at flow rates of 1 ℓ/sec. In those disease conditions, characterized by narrowing of the respiratory passageways, values as high as 11 cm $H_2O/\ell/sec$ have been measured.

All of these parameters then, resistances, compliances, volumes, rates, and pressures, establish the design requirements for mechanical respirators. In Part I, only a few typical values have been given together with a very abbreviated discussion of pulmonary physiology to provide an introduction to the problem of respirator design. Part II will expand on the parameters of respirator design and will briefly review the basic types of existing mechanical respirators to show how such requirements have been satisfied.

1.6 GLOSSARY

Alveoli - air cells of the lung.

Intrapleural space - the space between lungs and rib cage.

Intrapulmonary space - the space within the lungs.

Pulmonary - pertaining to the lungs.

Tracheobroncheal tree - the system of airways that allows the entrance of fresh air into the lungs.

Venous return - the blood flowing into the heart via the great veins.

PART II - DESIGN PARAMETERS AND DISCUSSION OF AUTOMATIC RESPIRATORS

by H. H. Straub

2.1 MECHANICAL ASPECTS OF RESPIRATION

Automatic respirators provide the lungs with the necessary amount of breathing gas to keep oxygen and carbon dioxide in the blood of the patient at normal levels. To understand the various methods of automatic respiration, a short engineering description of the mechanics of respiration will be presented.

The human pulmonary system, as described in Part I, may be represented by the double piston pump shown in figure 1. The thoracic cage is separated into two spaces representing the lungs and the intrapleural space. The downward movement of the lower piston (the thorax) lowers the pressure in the intrapleural space. Consequently, the upper piston will also move downward in an attempt to balance forces. The motion of the upper piston represents the expansion of the lungs. During the expiration phase, the intercostal muscles and diaphragm relax, and the lower (thorax) and upper (lung) pistons will return to their original positions because of the stored elastic forces present. The lungs then are passive elements which experience a volume change because of pressure variations in the intrapleural space. Also the exhalation phase is normally passive as the stretched elastic tissue of the thoracic cage and lungs contracts. The energy for exhalation has been supplied during the inspiratory phase.

In artificial respiration, there are two possible ways to ventilate a patient. For manual methods, the air reaches the lungs in a manner similar to that in spontaneous breathing; i.e., the thorax is forced to expand. In mouth to mouth respiration and automatic ventilation, air is forced into the patient under pressures large enough to overcome the resistance of the airways and the elastic forces of the lungs and thorax. Pressure has to be applied sufficiently long to insure a proper amount of lung inflation.

2.2 VENTILATION CHARACTERISTICS

It has been shown (ref 1) that the oxygen consumption of a person is related directly to minute ventilation and metabolic rate. Under normal conditions, an increased rate in oxygen and carbon dioxide exchange can occur only by breathing a greater amount of fresh air per unit time (ref 2). Only the air reaching the alveoli actually participates in the gas exchange process. Tidal volume and breathing rate are both variables.

The approximate relationship between minute volume, breathing rate, and metabolic rate is presented in figure 2. The data presented

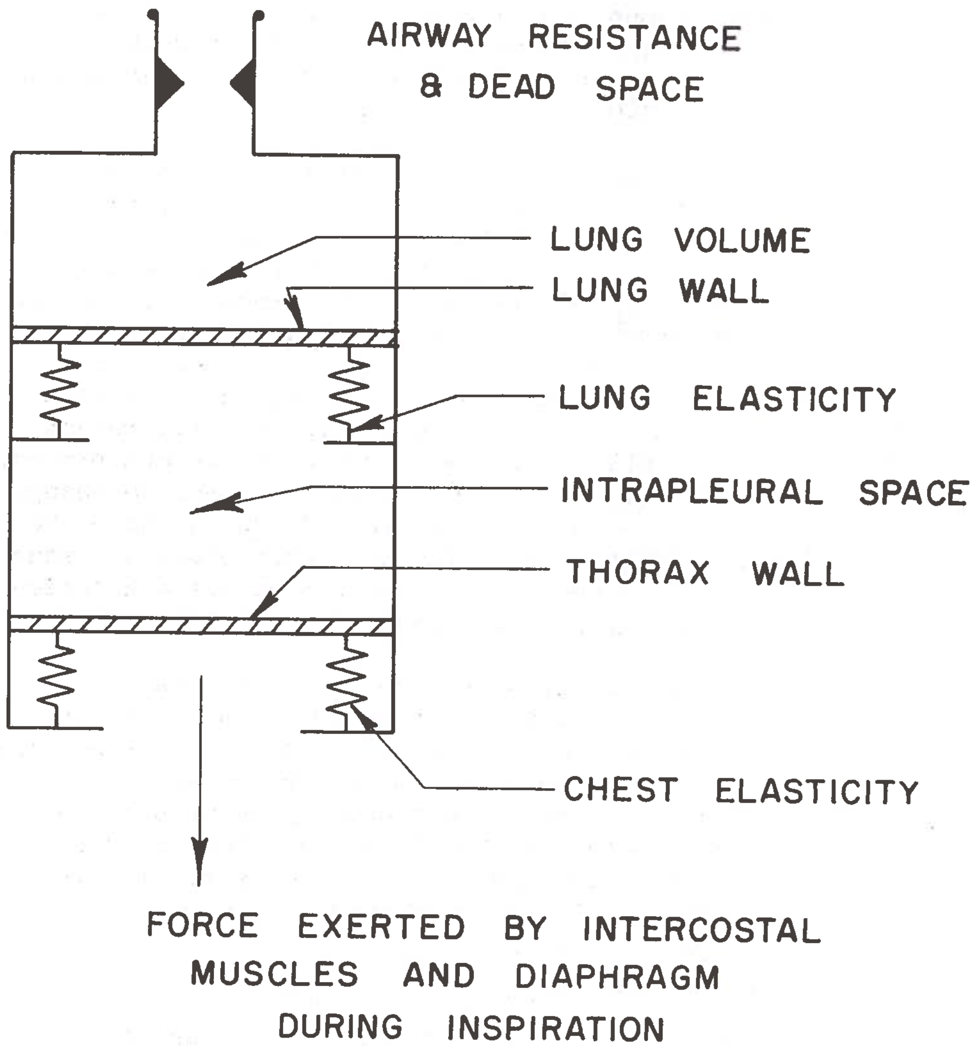

Figure 1. Mechanical equivalent of the human pulmonary system.

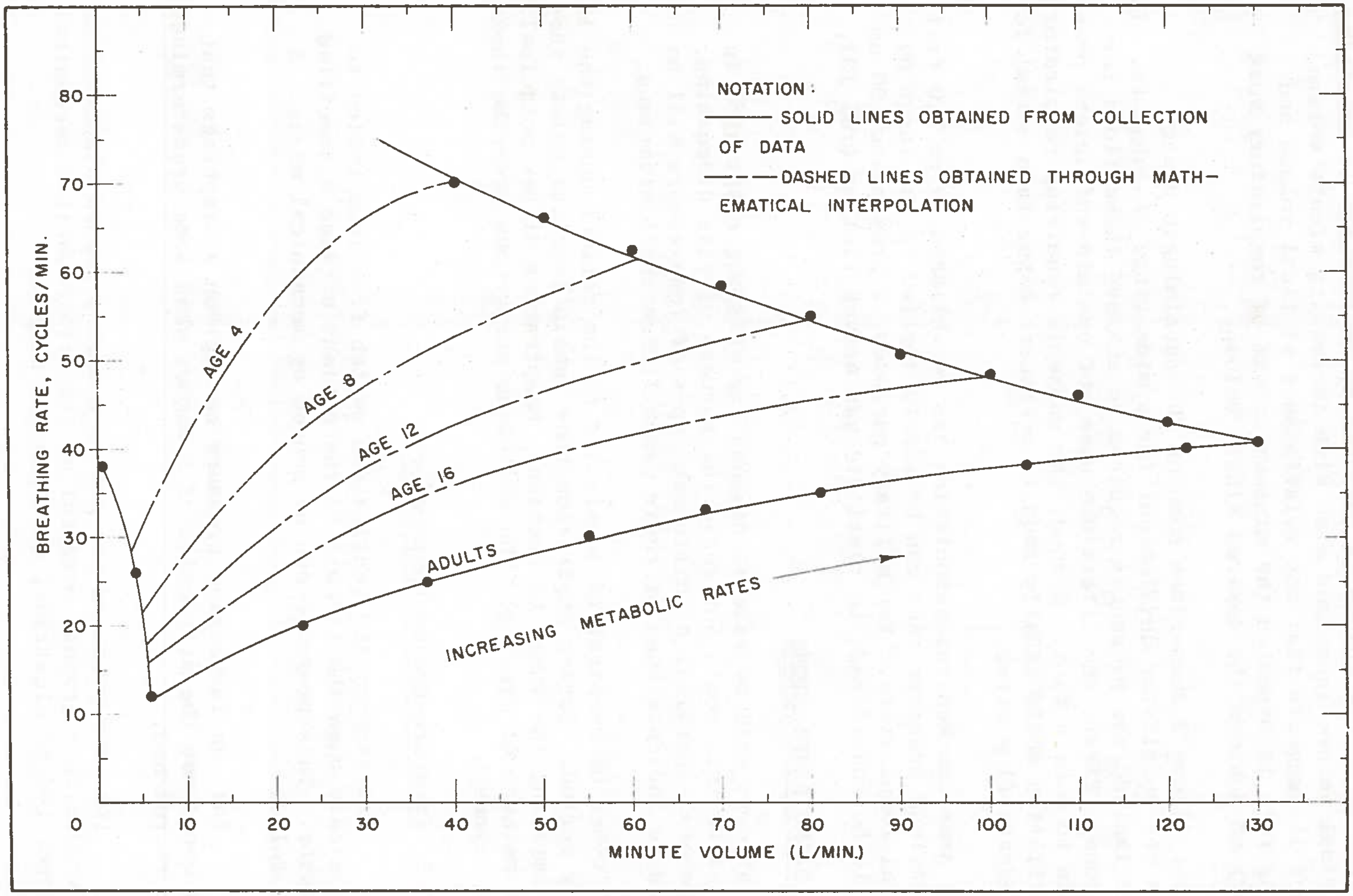

Figure 2. Human breathing parameters.

was obtained from references 3 through 10. The curves indicate that an increase in minute volume is achieved by an increase in breathing rate. Tidal volume increases also with increasing minute volume. Reference 11 suggests that the relationship of tidal volume and breathing rate is based on the minimum amount of respiratory work necessary to achieve the desired minute volume.

Thus, figure 2 summarizes some of the physiologic design criteria for respirator development for a wide range of subjects. It does not include the pressures required to achieve these flows for two reasons. First, the literature does not contain sufficient pressure data to make a plot. Second, the subjects requiring respirators for ventilation would usually require pressures other than normal for the necessary flow rates.

The American Medical Association has established 19 cm H_2O (ref 12) as the maximum pressure that can be safely applied to the lungs by mechanical respirators. For military purposes, a pressure of 50 cm H_2O has to be considered, to ventilate gas attack victims (ref 13).

2.3 EXISTING RESPIRATORS

No attempt will be made to discuss any existing respirator in detail, since this would not serve the purpose of this discussion. Only a general appraisal of different types of respirators will be presented to indicate some of their capabilities and limitations.

All types of respirators supply air to the patient during the inspiratory period. During expiration they remain inactive unless they help in emptying the lungs by suction. Respirators differ principally in their methods of cycling. The following paragraphs describe these principal types.

2.3.1 Pressure-Cycled Respirators

Pressure-cycled ventilators switch from inspiration to expiration only when the circuit to the patient attains a specified gas pressure. This pressure can be sensed by mechanical means. A few ways follow:

(a) An increasing pressure can act on a diaphragm that suddenly overcomes the attraction of a magnet when some predetermined pressure is reached.

(b) The pressure can act on a spring-loaded diaphragm or bellows producing a gradual movement of the device until a mechanical trip is operated or electrical contacts are closed.

(c) The pressure can displace a conducting liquid in a U-tube until electrical contacts are closed by the fluid.

Pressure-cycled respirators are usually fairly small unless they include a concertina bag to measure the volume of gas pushed into the lungs of the patient. Generally the end of the expiratory phase is regulated by adjusting the gas leak from a small reservoir. The inspiratory phase is initiated when a sufficiently low predetermined pressure is reached in the reservoir. Pressure-cycled respirators can be considered as constant total pressure sources that will switch once they are loaded by a certain static pressure. Mathematically, the inspiration phase of the respirator can be described by the following differential equation:

$$P = V/C + R(dV/dt) \qquad (1)$$

where

P = total pressure supplied by the respirator

V = delivered gas volume at time t

C = compliance of the lungs

R = linear resistance to airflow

dV/dt = airflow rate to lungs

The solution of this differential equation is

$$t_{in} = RC \ln \frac{1}{1 - V_t/PC} \qquad (2)$$

where

t_{in} = inspiratory time

V_t = tidal volume

For larger values of R, equation (2) shows that the inspiratory time increases. Consequently, the breathing rate decreases, and alveolar ventilation drops. By rearranging equation (2) as follows:

$$V_t = PC\left(1 - e^{-t_{in}/RC}\right) \qquad (3)$$

it can be seen that for a stiffer lung, i.e., a decreased C, with R and P remaining unchanged, a smaller tidal volume results. Correspondingly a shorter inflation time and a higher cycling rate are achieved. To some degree, smaller tidal volumes will be balanced by an increasing breathing rate to keep minute volume adjusted to the needs of the patient. However, the dead space in the breathing circuit and patient will impose limitations on such an automatic compensation.

Figure 3 is the schematic diagram of a pressure-cycle respirator. Pressure builds up in the chamber until the force exceeds the attraction between the magnet and opening the seal and letting the pressurized gas escape to the atmosphere.

2.3.2 Volume-Cycled Respirators

These respirators terminate the inspiratory phase when a preset volume of gas has been delivered to the subject. A bellows or piston is driven back and forth by an electric or pneumatic motor with a preset stroke volume. In several models, the movement of the bellows is reversed by a mechanical or electrical trip. Generally, these respirators can be considered as being driven by an infinite force, and hence, they are not load sensitive. Any obstruction in the air path to the lungs would lead to very high pressures, which might seriously injure the patient. Usually, this danger is eliminated by the introduction of a safety valve in the breathing circuit.

Respirators driven by electric motors are often large and bulky and possess only a very limited capability of altering the inspiratory-to expiratory-time ratio. Several of the respirators which are powered by pneumatic means are pressure-cycled as well as volume-cycled.

A schematic diagram of a volume-cycled respirator is shown in figure 4. A pin attached to the free end of the bellows strikes a cycling mechanism that interrupts the air flow to the cylinders.

Volume-cycled respirators are not affected functionally by leaks, since they will cycle only after they have delivered a preset volume regardless of where the gas is delivered. Existing models can ventilate a patient for an extended period of time.

2.3.3 Time-Cycled Respirators

In time-cycled respirators, inspiration and expiration end after some predetermined time set by the controls on the apparatus. Some respirators use pneumatically operated timing mechanisms such as windshield wiper motors or plenum chambers in which slowly rising and falling pressures are sensed mechanically. Other timing mechanisms are electrically or electromechanically operated. Flow rates and pressures are set according to the needs of the patient. Several of these respirators are quite large and difficult to transport easily.

A schematic diagram of a time-cycled respirator is shown in figure 5. Slowly increasing and decreasing pressures in the plenum chamber are controlled by the needle valve. These pressures move the diaphragms back and forth and thus the air flow to and from the piston is timed.

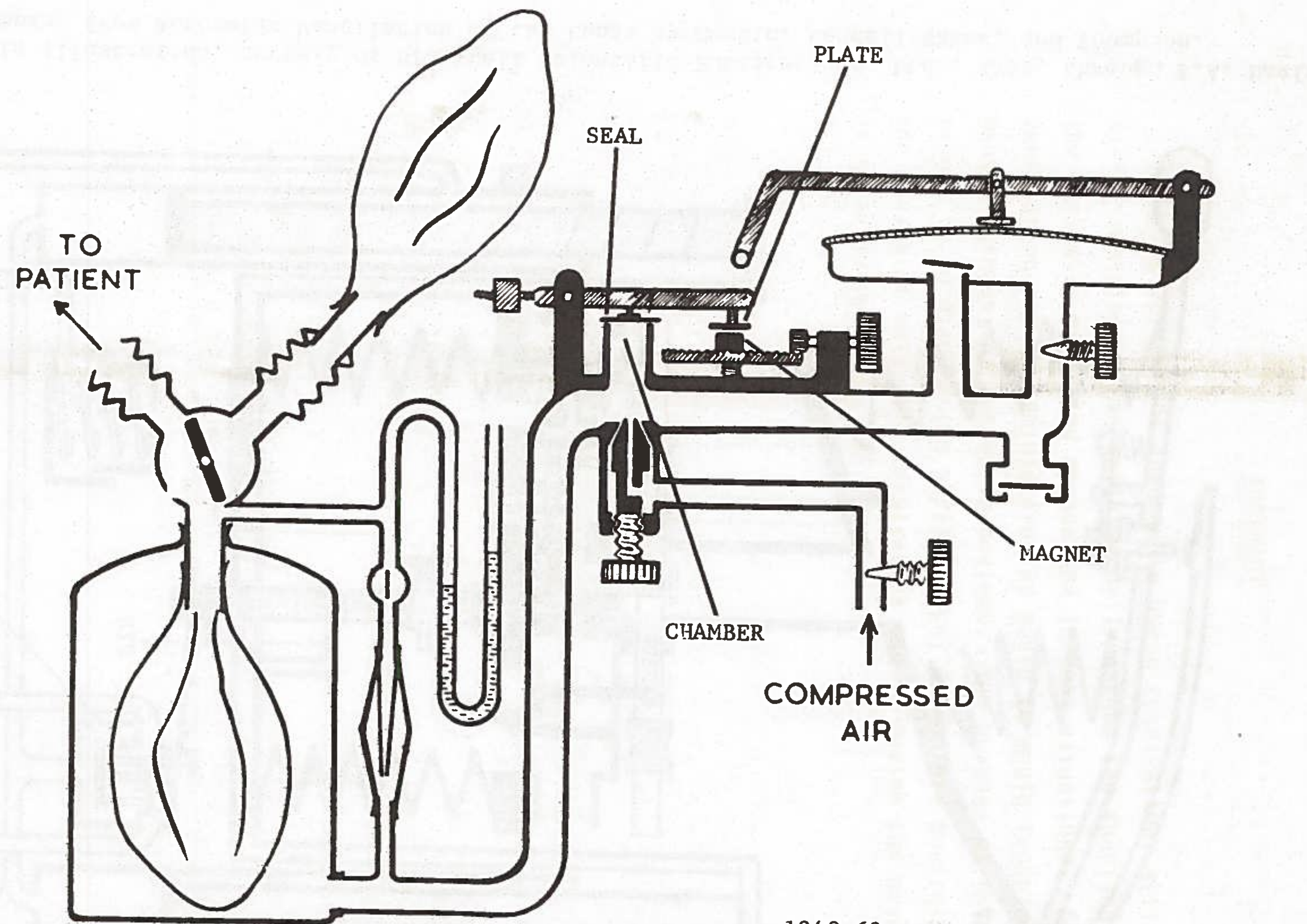

Figure 3. A pressure-cycled respirator.

This illustration courtesy of Blackwell Scientific Publications, Ltd., 1959 through F.A. Davis Company from Automatic Ventilation of the Lungs by Mushin, Rendell-Baker, and Thompson.

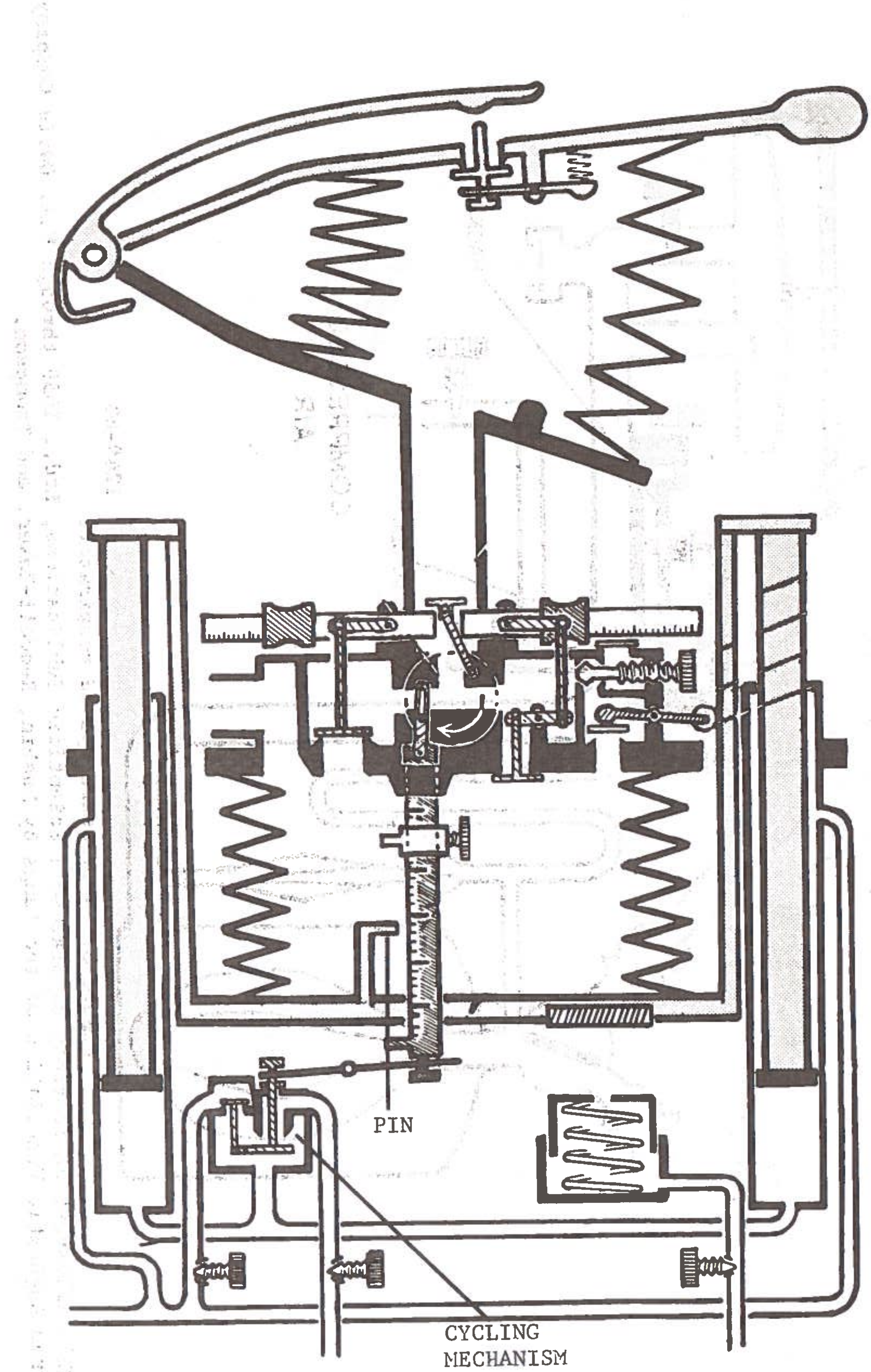

Figure 4. A volume-cycled respirator.

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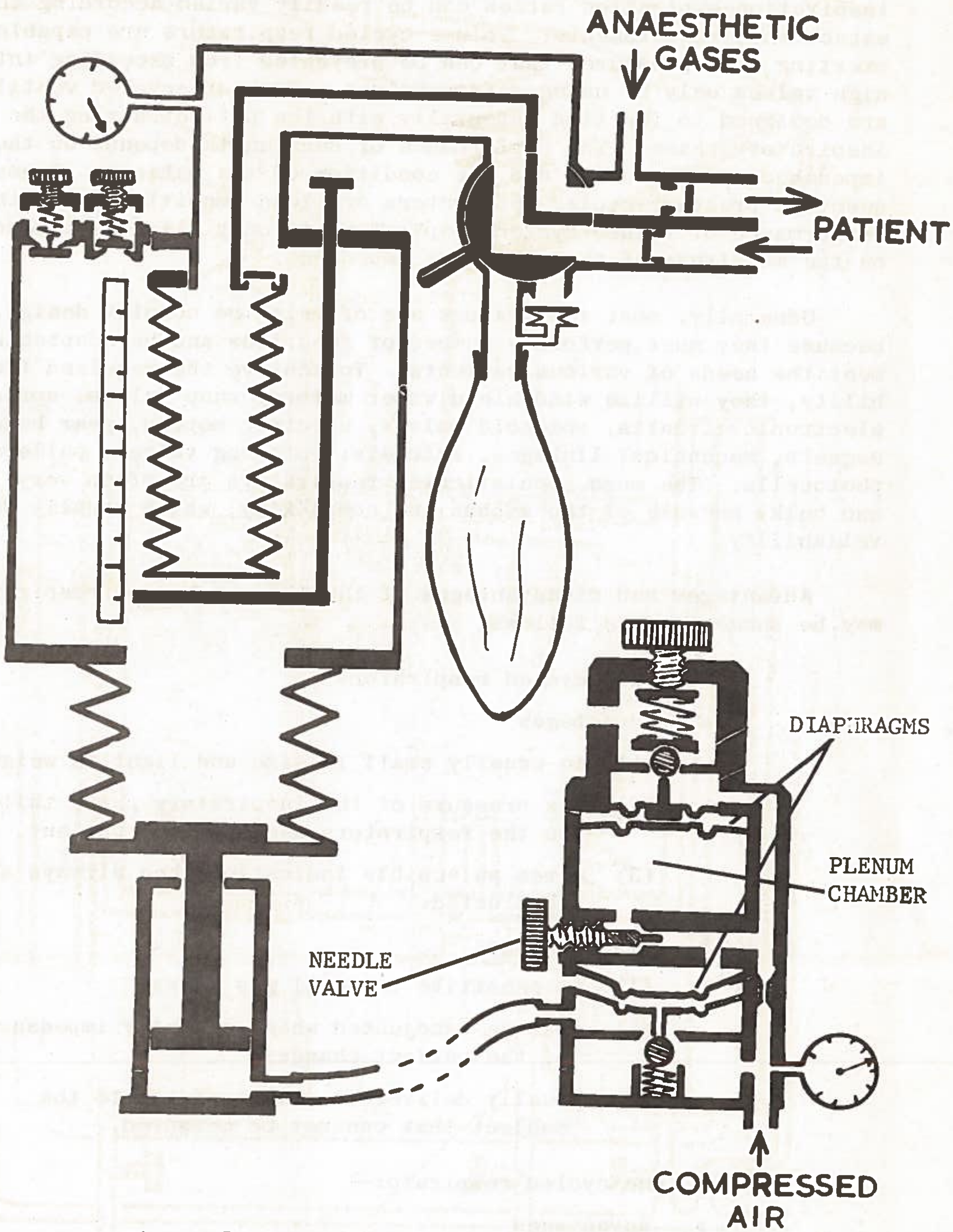

Figure 5. A time-cycled respirator.

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2.4 DISCUSSION

Existing respirators can adequately meet the respiratory needs of the patient. Flow rates, tidal volumes, breathing rates, and inspiration-expiration ratios can be readily varied according to established requirements. Volume-cycled respirators are capable of exerting high pressures that can be prevented from exceeding intolerably high values only by using safety valves. Pressure-cycled ventilators are designed to function integrally with the patient during the inspiratory phase. The performance of such units depends on the impedance of the tubing and the condition of the patient. Consequently, pressure-cycled respirators are load sensitive while the performance of volume-cycled respirators is only slightly dependent on the magnitude of the pulmonary impedance.

Generally, most respirators are of relative complex design, because they must perform a number of functions and be adaptable to meet the needs of various patients. To achieve the required flexibility, they utilize windshield wiper motors, snap valves, springs, electronic circuits, solenoid valves, electric motors, gear boxes, magnets, mechanical linkages, ratchets, rotating valves, pulleys, and photocells. The more sophisticated respirators are often very large and bulky because of the mechanical complexity, which usually degrades reliability.

Advantages and disadvantages of the three types of respirators may be summarized as follows:

Pressure-cycled respirator—

a. advantages

(1) is usually small in size and light in weight.

(2) has pressure of the inspiratory phase tailored to the respiratory needs of the patient.

(3) gives an audible indication when airways are obstructed.

b. disadvantages

(1) is sensitive to small gas leaks.

(2) must be readjusted when pulmonary impedance of the patient changes.

(3) usually delivers a volume of gas to the subject that can not be measured.

Volume-cycled respirator—

a. advantages

(1) is insensitive to small gas leaks.

(2) requires no readjustment when pulmonary impedance of the patient changes.

(3) delivers a measurable volume of gas to the patient.

b. disadvantages

(1) usually, but not always, bulky in design.

(2) does not give an audible indication of airway obstruction.

Time-cycled respirator—

a. advantages

(1) operation is insensitive to small leaks.

(2) delivers a known volume of gas to the patient.

(3) need not be readjusted when the pulmonary impedance of patient changes.

b. disadvantages

(1) is large in size when designed to perform variety of duties.

(2) gives no audible indication of airway obstruction.

It is intended that this survey of the advantages and disadvantages of existing respirators and the ventilation requirements summarized in the body of the text will provide a basis for the design of fluid amplifier ventilators for Army field use.

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