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Pulmonary Function Evaluation in Air and Space Flight

ROSCOE G. BARTLETT, JR., Ph.D.

IDEAL pulmonary function monitoring for air and space flight is one which will permit constant monitoring with a minimum of equipment on the pilot or astronaut. Also desirable is a technique which places small requirements on the pilot or astronaut. Within these limitations it would be desirable, of course, to have as broad a readout as possible. Because of the difficulty of administering individual tests, and because of the limited readout from them, the usual pulmonary function tests are not adequate for inflight evaluation of pulmonary function. What is required, then, is a new concept in pulmonary function evaluation which is adaptable to continuous inflight monitoring. The velocity-volume (V′-V) loop gives promise of being such a test. Since the V′-V loop technique is a new concept in pulmonary function monitoring, it will be necessary to describe first the nature of the test and second, its adaptation to inflight monitoring will be presented.

Opinions or conclusions contained in this paper are those of the author and do not necessarily reflect the views or endorsement of the Navy Department.

From the U. S. Naval School of Aviation Medicine, U. S. Naval Aviation Medical Center, Pensacola, Florida.

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I. THE VELOCITY VOLUME (V′-V) LOOP TECHNIQUE

Procedure

The Apparatus

The V′-V loop may be constructed by plotting temporarily aligned values for breath velocity and breath volume. Clinically, it is most easily obtained by feeding the transduced velocity and volume signals into the two axes of the cathode ray oscilloscope. For instrumentation simplicity in inflight monitoring, the loop is synthesized, as described below, from flow and volume values obtained from a telemetered pneumotachograph. In laboratory experiments the Servospirometer (Custom Engineering and Development Company) is used. This provides both velocity and volume signals which are linear and which are fed into an oscilloscope. If an oscilloscope is to be used for instantaneous plotting of the velocity-volume relations, a linear flowmeter must be used.

Testing Methods

Laboratory test methods will be described briefly to indicate the rationale for loop construction.

The subject is asked to place his mouth on the wide bore, low resistance tube from the spirometer (Servo- or Wedge) and perform a forced maximum inspiratory and a forced maximum expiratory fast vital capacity maneuver. Photographs are taken of the breath loop from

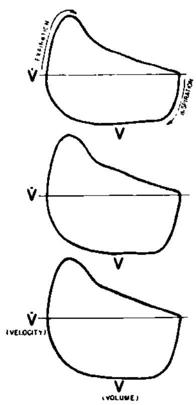


Fig. 1. Maximum V′-V loops from same individual recorded on three different days. Arrows indicate the inspiratory and expiratory and portions of the envelope.

the face of the oscilloscope. After recording the forced vital capacity (maximum) V′-V loop the subject is asked to breathe normally without removing his mouth from the spirometer tube. Recovery from the forced breathing is rapid, and after a few breaths the subject has returned to normal resting breathing. The resting tidal (resting) loops are now seen to trace nearly identical paths; the shutter is opened for a single breath, and the resting V′-V loop recorded superimposed on the maximum V′-V loop. When the two loops are recorded together, the lung volume measurements obtained from the usual spirogram may be measured from the two V′-V loops.

Velocity-Volume Loop Analysis

Loop Contour

For a given subject the maximum V′-V loop has a marked individualistic contour. Loops taken on different days are nearly identical in all of the contour details. In Figure 1 are shown loops recorded on three different days for the same individual. The marked similarity of the loops is obvious. Although loops for normal individuals have very characteristic contours, loops from patients with obstructive respiratory diseases are easily distinguishable from the normal loops. The contour *per se*, then, has significant diagnostic value without resorting to any additional analysis. In Figure 2 are shown V′-V loops from patients with aging and with

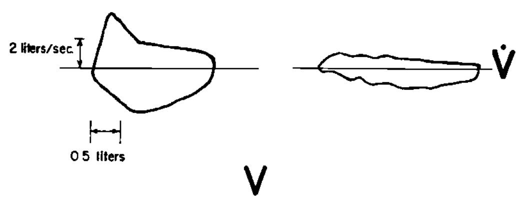


Fig. 2. Maximum V′-V loops from patients with aging (*left*) and respiratory disease (*right*).

respiratory disease. A comparison with the normal loops in Figure 1 indicates the altered contours and lower velocities of the loops associated with pulmonary pathology. Since the form of the V′-V loop is determined by breath volume, breath acceleration, and their change with time, it is apparent that the loop envelope should reflect disease processes or physiologic changes that might occur with flight stresses which affect either the magnitude of lung volume change or the rate of these changes during the forced vital capacity movements.

Lung Volumes

Vital Capacity. The x axis of the tracing is volume. Since the y axis is velocity, with an established zero velocity line, the beginning and end of inspiration and expiration are clearly indicated. The distance between these two points along the volume axis, of course, represents the vital capacity when the loop is recorded from forced vital capacity breaths.

Expiratory Reserve Volume. When the resting tidal V′-V loop is recorded superimposed on the maximum V′-V loop without any loss or addition to lung air, the relative position of the two loops permits a measurement of the subdivisions of lung air (Fig. 3). As indicated in this figure, expiratory reserve volume is delimited by the volume displacement of the end-expiratory points for the resting loop and the maximum loop.

Inspiratory Reserve Volume. Inspiratory reserve volume is defined by the volume displacement of end-inspiratory points for the maximum and resting loops (Fig. 3).

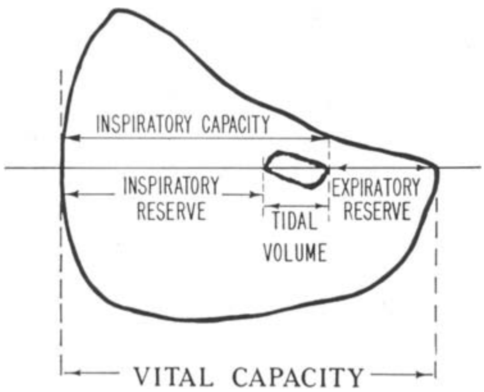


Fig. 3. Resting V′-V loop superimposed on maximum loop, showing use of loops for obtaining values for subdivisions of lung air.

Inspiratory Capacity. The measurement of inspiratory capacity is shown diagrammatically in Figure 3 as the volume displacement of end inspiration on the maximum loop and end expiration on the resting loop.

Timed Vital Capacities

Expiratory Vital Capacity Time (EVCT). The elapsed time for the forced expiratory vital capacity is not easily determined. The final lung volume is approached very slowly and the exact time at which it is reached is not readily determined. For this reason the Timed Vital Capacity test has been introduced. This test avoids the difficulty of ascertaining the exact point at which the final lung volume is reached by measuring the time for delivery of a given percentage of the vital capacity. The parameters recorded in the V′-V loop make possible a precise measurement of the time required for delivering the full vital capacity with no problem involving the difficulty of ascertaining the point in time at which the final lung volume is attained. Since the area of the V′-V loop is equal to the velocity (V′) times the volume (V), it is obvious that one may substitute V/T for V′ and solve for T as shown in Figure 4.

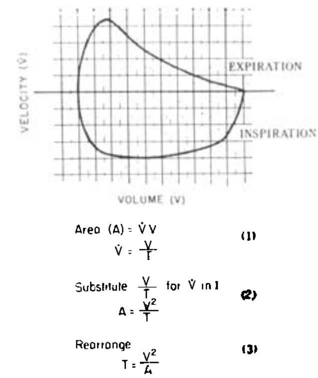
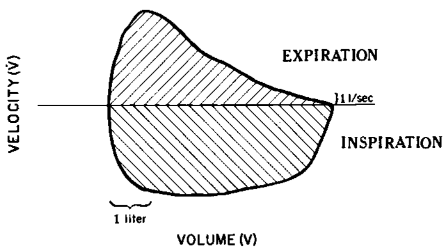


Fig. 4. Use of the maximum V′-V loop for calculating the time required for breath movement.

This time value, as is readily apparent, is a calculated time, and its magnitude is not significantly altered by "straining" at the end of expiration since neither of the parameters used for its calculation is altered by "straining."

Inspiratory Vital Capacity Time (IVCT). The magnitude of the maximum breathing capacity (MBC) is determined by the rate of volume displacement during both inspiration and expiration. When it is not convenient or feasible to use the MBC test, the mechanical capacity of the breathing mechanism is frequently assessed by use of the Timed Vital Capacity test. This test uses an expiratory vital capacity movement; thus the breathing capacity is assessed from observations on only half the breathing cycle. The V′-V loop may be used, as shown in Figure 5, for measuring inspiratory vital capacity time (IVCT) as well as EVCT. Since this is a calculated time, its magnitude is not altered by straining at the end of inspiration. The time for the entire breath may also be calculated from the V′-V loop in a single operation. The volume figure used in the formula, of course, is twice the vital capacity because this volume is moved first in and then out of the lungs.

Timed Vital Capacity. The information obtained from the usual Timed Vital Capacity test may be obtained directly from the V′-V loop. In the use of the loop, however, the time for



$$\text{For Expiration EVCT} = \frac{V^2}{A} = \frac{5^2}{2075} = 1.20 \text{ sec}$$

$$\text{For Inspiration IVCT} = \frac{V}{A} = \frac{5^2}{3415} = 0.73 \text{ sec}$$

Fig. 5. Use of the maximum V′-V loop for expiratory vital capacity time (EVCT) and calculating inspiratory vital capacity time (IVCT).

delivery of a specified lung volume is measured rather than the percentage of the vital capacity delivered in a given time. For instance, the time may be calculated for delivering 70 per cent of the vital capacity.

The above formulae are only approximations in that they are true only when V′ is constant and reasonably true only when V is relatively constant. The errors inherent in this approximation do not seem to be too great for practical use. The exact time may be found by use of differential equations. However, for the purposes of monitoring of the astronaut or pilot, the simplified approximation formulae seem quite adequate.

Reserve Velocities

The usual analysis of breathing function includes a subdivision of the lung volume which indicates inspiratory and expiratory reserve volumes. Changes in these reserve volumes with disease processes are frequently of diagnostic value. As a functional evaluation, rather than a simple static index as provided by the reserve volume measurements, the inspiratory and expiratory reserve velocities may be useful. Although these are not easily measured by the usual testing technique, their magnitudes are immediately apparent when both the maximum and tidal V′-V loops are recorded together, as illustrated in Figure 6. As seen there, the expiratory reserve velocity for the normal subject is much less than the inspiratory reserve velocity. From the few measurements made, both are altered with disease processes, and in the patient with emphysema the expiratory reserve velocity may approach zero. Additional studies are needed to indicate the usefulness of the reserve velocity measurements in pulmonary function evaluation.

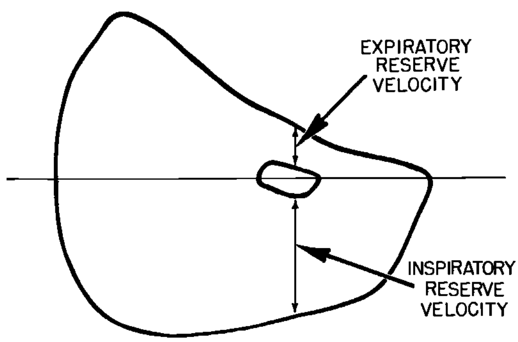


Fig. 6. Use of the maximum and tidal V′-V loops for measuring inspiratory and expiratory reserve velocities.

Maximum Performances

The effects of disease processes on maximum performances are frequently more dramatic and revealing than are their effects on mean or average performances. Therefore, there might well be some significance in such observations as maximum inspiratory and expiratory accelerations and maximum inspiratory and expiratory velocities. Both peak velocity and acceleration figures may be obtained from the V′-V loop. Velocity values are read directly from the loop, and the maximum inspiratory and expiratory velocities are indicated by the peak values during inspiration and expiration.

Acceleration values cannot be read directly from the V′-V loop. In Figure 7 is shown a procedure for obtaining a value which is a function of the acceleration. The value obtained does not really represent the acceleration over the straight segment of the V′-V loop. The actual acceleration is changing exponentially, but the value does represent a function of acceleration and it is useful for comparison purposes. The actual acceleration values at any volume point can be found by use of the calculus.

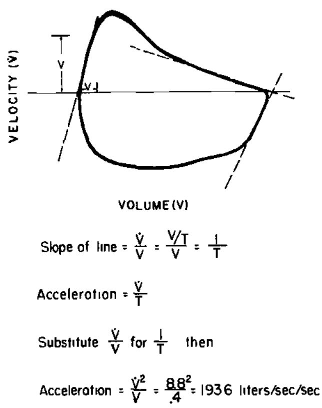


Fig. 7. Procedure for calculating acceleration from the V′-V loop. Figures inserted in formula are from slope at beginning of expiration.

Maximum Breathing Capacity Prediction

Rationale. In Figure 8 is shown a vital capacity (maximum) V′-V loop on which is superimposed V′-V loops recorded during the execution of an MBC test. The relationship of the MBC loops to the maximum loop is seen easily. The MBC loop follows the envelope of the maximum loop until it breaks away abruptly to cross the zero flow ordinate and meets the maximum vital capacity V′-V envelope for the other half breath cycle. Since the MBC V′-V loop can be roughly approximated by erecting perpendiculars at end inspiration and end expiration on the volume axis, as shown in Figure 9, it becomes apparent that perpendiculars delimiting several tidal volumes may be erected to estimate the maximum breathing capacity at a number of breathing frequencies. An obvious problem arises as to the optimum placement of the tidal volume on the vital capacity volume axis. The procedure for determining the optimum limit of inspiration and the prediction of the MBC at a number of breathing frequencies from the V′-V loop is detailed elsewhere[1] and briefly summarized below.

As in the method of Bernstein and Kazantzis,[3]

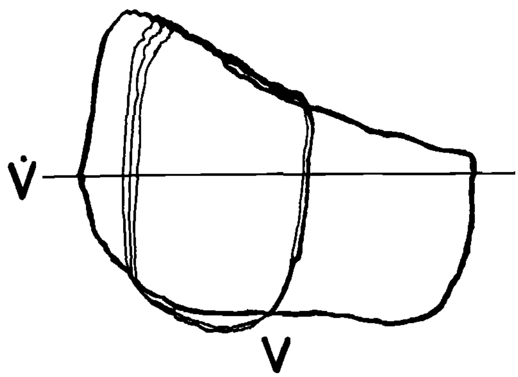


Fig. 8. Maximum V′-V loop on which are superimposed several maximum breathing capacity V′-V loops. Note maximum V′-V loop overshoot.

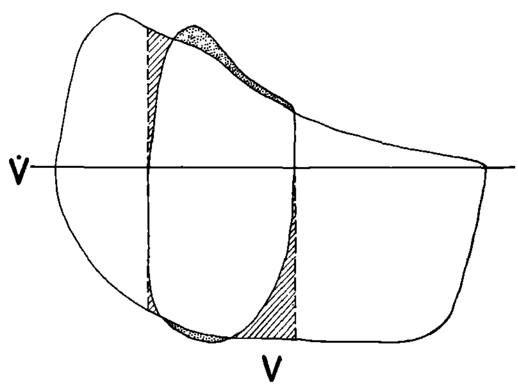


Fig. 9. Maximum V′-V loop and MBC V′-V loop superimposed to show the V′ and V relations. Perpendiculars at extreme of MBC tidal volume show technique for approximating the MBC V′-V loop. Importance and relations of shaded areas and MBC V′-V loop overshoot discussed in Reference 1.

it is assumed that air exchange is made over that portion of the vital capacity, yielding the highest ventilation. In the use of the V′-V loop what this means, of course, is that when a tidal volume is assumed, it must be ascertained as to where on the vital capacity axis this volume can be moved in the shortest time, thus yielding the highest breathing frequency and largest predicted MBC for this tidal volume. As seen from a study of Figure 9, this minimum time is derived by finding the location of the assumed tidal volume on the vital capacity axis where perpendiculars at the inspiratory and expiratory ends of the tidal volume embrace the largest combined inspiratory and expiratory areas. From previous experimentation[2,3] and from superimposition of the maximum V'-V loop and MBC V'-V loops (Fig. 8), there is justification for the above rationale in MBC prediction. The technique for finding the optimum placement of the assumed tested volume on the vital capacity axis is described briefly in the following section.

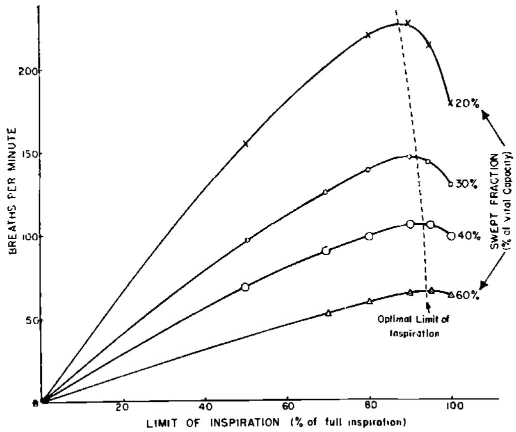


Fig. 10. Family of breathing frequency, limit of inspiration curves showing optimum limit of inspiration for a number of swept fractions.

Family of Curves Showing Optimum Limit of Inspiration for Each Tidal Volume. The maximum V'-V loop is plotted on a grid to facilitate velocity and volume and area measurements. The optimum limit of inspiration (i.e., the percentage of full inspiration at which an inspiration must cease to yield the largest tidal volume) or, as it has been previously referred to in this discussion, the optimum placement of the tidal volume on the vital capacity axis, is found for a progression of tidal volumes. Tidal volumes of 20, 30, 40, 60, and 80 per cent of vital capacity were used. A tidal volume is selected and then placed on the vital capacity axis with the limit of inspiration sequentially at 100, 95, 90, 80, 70, and 50 per cent of full inspiration. At each limit of inspiration perpendiculars to the volume axis are drawn at each end of the tidal breath and the enclosed area found. By use of the formula developed in Figure 4 the time for moving the breath at this limit of inspiration is calculated. From this information the maximum number of breaths possible for the total volume at this limit of inspiration is obtained. These data are plotted as shown in Figure 10. The limit of inspiration is then moved to another point and the procedure repeated. Thus for each tidal volume one curve of a family of curves is plotted. As seen in Figure 10 a family of curves shows the optimum limit of inspiration for each tidal volume.

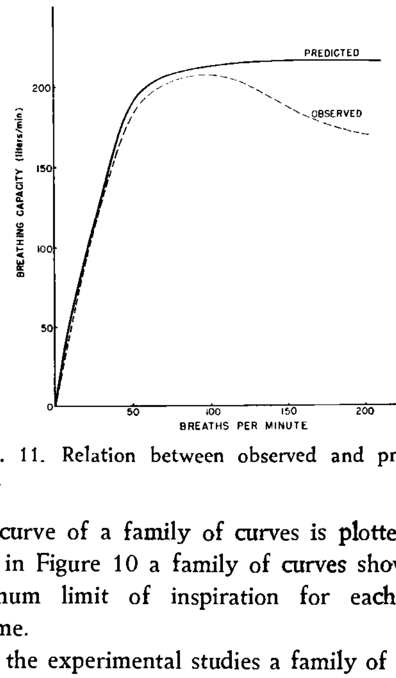


Fig. 11. Relation between observed and predicted MBC.

In the experimental studies a family of curves was constructed for each experiment. Actually, for normal subjects the curves are so similar that for routine testing or inflight pulmonary function evaluation the limits of inspiration to use for each tidal volume in MBC prediction may be obtained from a single average family of curves with negligible error involved.

Predicting the MBC. The optimum limit of inspiration for each breathing frequency having been determined, it becomes possible to construct a predicted MBC, breathing-rate curve. One of a series of tidal volumes is selected and by interpretation from the optimum limit of inspiration curves, placed on the vital capacity axis with the inspiratory end at the proper limit of inspiration. Perpendiculars are erected at either end of the tidal breath, the embraced area measured, and the time for the complete breath and the MBC calculated. This procedure is repeated for each of the selected tidal breaths in the series. When plotted on MBC breathing-rate coordinates, the predicted MBC curve over a wide range of breathing frequencies is constructed. A typical relationship of the predicted and observed MBC breathing-rate curves is shown in Figure 11. In most subjects there is a somewhat greater difference in the MBC values at breathing frequencies of over 100 breaths per minute than shown here. Observed MBC values were obtained with the usual fifteen-second clinical test.

A detailed description of the MBC prediction technique, of which the above is a brief condensation, appears elsewhere.[1] In that report the relationship between predicted and observed MBC values, the phenomenon of maximum V′-V loop overshoot, and the relation of pulmonary function and MBC prediction are discussed.

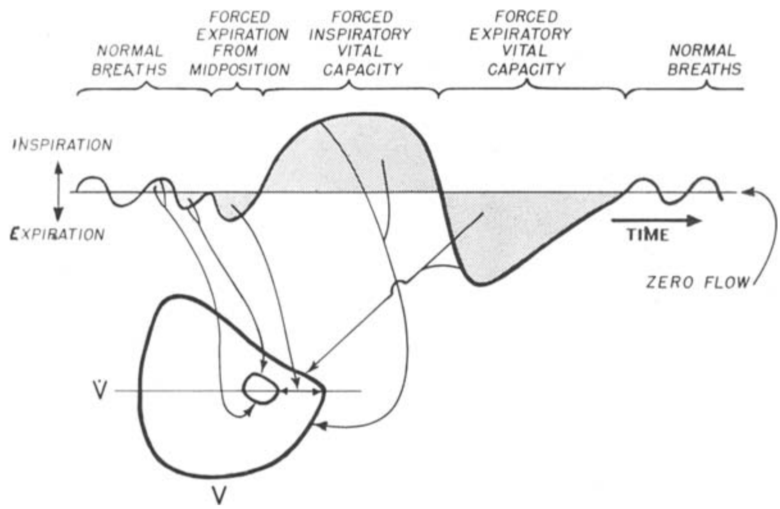


Fig. 12. Construction of the V′-V loop from the pneumotachogram. Velocity values are obtained directly from the pneumotachogram. Volume values are obtained by integration of the velocity pattern.

II. PULMONARY FUNCTION EVALUATION OF THE PILOT OR ASTRONAUT IN FLIGHT

Occasional Monitoring of Pulmonary Function in Flight

The Equipment

A pneumotachograph, transducer, and appropriate readout are required. The pneumotachograph and transducer may be supplied as a single unit. With commercially available material it would weigh about 12 ounces; with miniaturization, likely much less. The type of amplifier needed is now available in miniature form with a weight of about 8 ounces. A single telemetry channel of reasonably broad-band width is required.

The equipment could be integrated into the existing life support system as follows: For occasional monitoring there would be no change in suit, helmet, or support system. The pneumotachograph (perhaps with attached transducer) would be placed near the pilot or astronaut. At specified times the aviator or astronaut would open the face plate, or remove the mask and place the pneumotachograph to his mouth. A minute or less of monitoring would provide adequate data for analysis. The problems involved are obvious and differ with different types of life support equipment. This approach is noted only to indicate its possibility and not its advisability. It is desirable only from the viewpoint that there is no alteration of the existing life support equipment. Where suit and helmet are worn only for emergency, as in the Mercury capsule, this approach might be used. When oxygen must be breathed, the approach obviously is limited. The techniques for continuous monitoring of pulmonary function described below seem much preferred.

TABLE I. INDICES OF PULMONARY FUNCTION OBTAINED FROM THE MAXIMUM AND TIDAL V′-V LOOP

1. Loop envelope contour which has significant diagnostic value in itself	
2. A complete spirogram including (a) Vital capacity (b) Expiratory reserve volume (c) Inspiratory reserve volume (d) Inspiratory capacity (e) Tidal volume (f) Evidence of air trapping	3. Breath timing including (a) Information obtained from the timed vital capacity (b) Exact time for an inspiratory vital capacity (c) Exact time for an expiratory vital capacity
4. Inspiratory reserve velocity	5. Expiratory reserve velocity
6. Maximum expiration velocity	7. Maximum inspiration velocity
8. Breath acceleration during any phase of breathing cycle	9. A very reliable prediction of the maximum breathing capacity

Information From the Readout

Breathing frequency, tidal volume, minute volume, and breath velocity and acceleration can be monitored from the control (normal breathing) velocity trace. When the pilot or astronaut periodically performs the following simple breathing maneuver, a number of additional parameters may be evaluated. After a normal exhalation, all of the air is forced from the lungs after which, with maximum force and speed the lungs are completely filled, and then with continued maximum effort the lungs are completely emptied. The information so obtained will permit the construction of a maximum velocity-volume (V′-V) loop and normal tidal loop (Fig. 12) from which the detailed information described above and outlined in Table I can be obtained.

Continuous Monitoring of Pulmonary Function in Flight

Without Monitoring O_2 Consumption

To permit continuous monitoring of pulmonary function certain modifications in the existing life support equipment would have to be made. The changes are relatively simple and few. When full pressure suits are used, as in the Mercury flights, oxygen flow in the suit (for ventilation) and in the helmet (for breathing) must be separated by a neck seal, as illustrated in Figure 13. In this modification, oxygen from the already employed conditioning circuit is drawn, on demand, through the helmet and expired again into the circuit. The modification of the helmet to permit continuous monitoring is shown in Figure 14. It should be stressed that with the modification no attention of the pilot or astronaut is needed for continuous monitoring of the breathing pattern. Occasionally, a voluntary respiratory maneuver (Fig. 12) would permit the evaluation of a number of additional parameters from the V′-V loop.

In the use of conventional helmet the oxygen flow to the mask is already separated by a face seal from the airflow in the suit used for ventilation. The helmet need only be modified, as illustrated diagrammatically (Fig. 14) for pulmonary function evaluation.

Addition of the pneumotachograph facility, to the regular A13-A oxygen mask permits pulmonary function evaluation with this type of life support equipment.

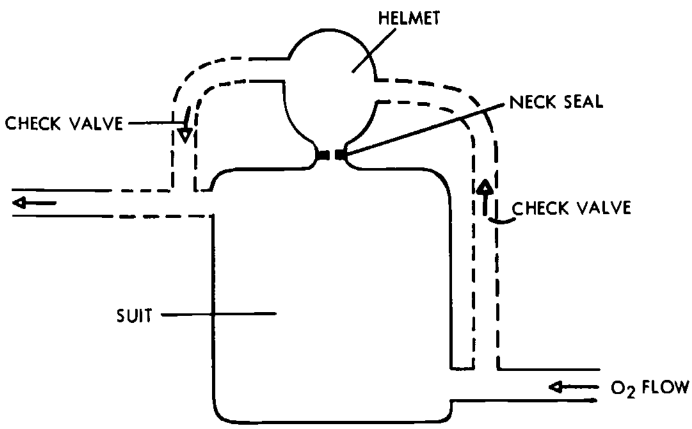


Fig. 13. Block diagram of the modifications of the life support equipment necessary for continuous monitoring of pulmonary functions. Dotted lines indicate modifications in oxygen circuit.

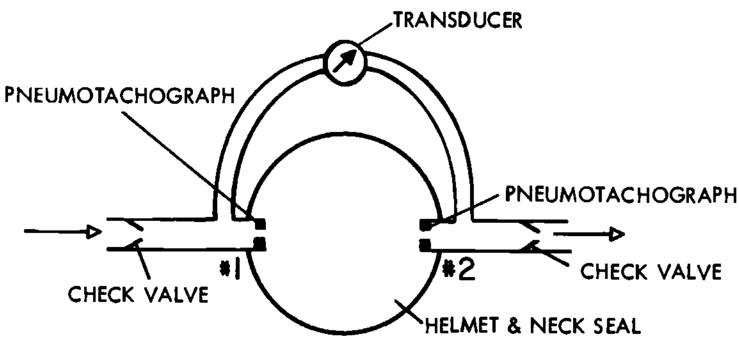


Fig. 14. Diagram of adaptations for breath velocity recording. During inspiration there is no flow through the pneumotachograph at No. 2. In this static condition, the pressure at the pressure tap at No. 2 is the same as it is on the helmet side of the pneumotachograph at No. 1. Therefore, the pressure differential across pneumotachograph at No. 1 monitors inspiratory velocity. By similar reasoning, pressure drop across the pneumotachograph at No. 2 during expiration monitors expiratory velocity.

With Monitoring O_2 Consumption

The same basic respiration equipment as described above is needed. In addition, for the Mercury life support equipment, there must be the modifications shown diagrammatically in Figure 15. Modifications for other types of equipment are similar. In effect, a typical closed circuit system is required. With CO_2 and H_2O removed, the O_2 would be rebreathed. Only a make up of O_2 would be required. Rate of O_2 use could be determined easily by following the pressure drop in the storage cylinder. This pressure drop, of course, would be telemetered.

In addition to O_2 consumption itself, the coefficient of oxygen utilization may now be calculated. This gives information concerning pulmonary diffusion. However, since hyperventilation also changes the coefficient, firm conclusions cannot always be drawn without a knowledge of end tidal or arterial CO_2 tensions.

CONCLUSIONS

It is thus seen that continuous recording from the pneumotachograph, with only occasional attention by the pilot or astronaut, permits the evaluation of a number of respiratory parameters. Only a single transducer and channel are required. Properly employed, the approach as outlined permits an inflight evaluation of a large number of factors, some of which are not

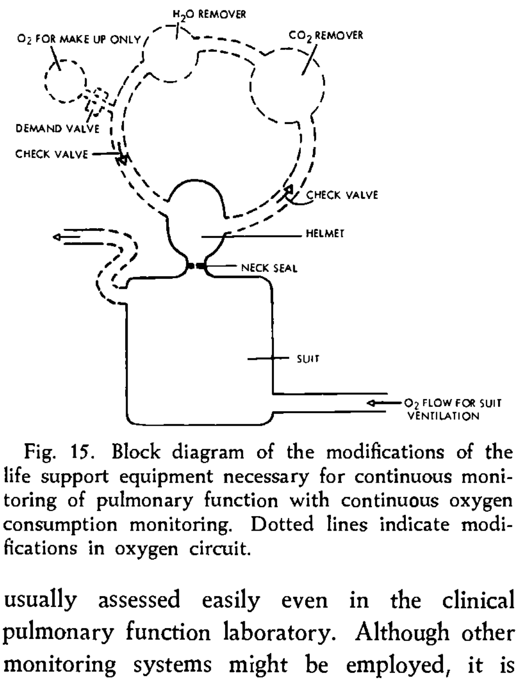


Fig. 15. Block diagram of the modifications of the life support equipment necessary for continuous monitoring of pulmonary function with continuous oxygen consumption monitoring. Dotted lines indicate modifications in oxygen circuit.

usually assessed easily even in the clinical pulmonary function laboratory. Although other monitoring systems might be employed, it is felt that probably no other system likely would provide so much information with so little instrumentation and involvement of action by the pilot or astronaut. Of course, considerable data manipulation by the ground crew is required to provide appraisal of all the parameters, but the dominating considerations here appear to be for simplicity of instrumentation and diversity and meaningfulness of the composite readout.

SUMMARY

Because of the difficulty of administering individual tests, and because of the limited readout from them, the usual pulmonary function tests are not adequate for inflight evaluation of pulmonary function. Therefore, the need for a pulmonary function test adaptable for inflight monitoring and yielding a broad readout was indicated.

The velocity-volume (V′-V) loop, a composite pulmonary function test adaptable to inflight monitoring, gives promise of being such a test. From two breaths, a maximum and a resting tidal, a number of pulmonary function parameters may be evaluated. First, the loop contours, *per* se, have significant diagnostic values. A complete spirogram analysis is obtained also, including measures of vital capacity, expiratory reserve volume, inspiratory reserve volume, inspiratory capacity, tidal volume, and evidence of air trapping. A number of breath timings are possible including the timed vital capacity. In addition, a new measurement is provided, that of an assessment of inspiratory and expiratory reserve velocities. Breath velocities are continually recorded. The breath acceleration may be calculated during any phase of the breathing cycle. Also, the maximum breathing capacity may be reliably predicted.

The V′-V loop may be synthesized from a single telemetered signal, breath velocity. Only brief attention from the aviator or astronaut (for two breaths) is necessary. The broad spectrum of parameters assessed from the readout is possible because of a new approach using a newly developed composite pulmonary function test.

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