

Automated System for Direct Measurement and Feedback of Total Respiratory Resistance by the Forced Oscillation Technique

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ABSTRACT

An automated system for obtaining a direct measurement of total respiratory resistance (R_T) is presented. A polygraph and digital computer are used to filter and quantify the pressure and flow outputs of a forced oscillatory device to determine R_T . Functional descriptions of the complete hardware system and of the computer software are included. The measurement of R_T is viewed as providing a sensitive and relatively unobtrusive means for investigation of psychophysiological precipitants of subclinical variations in bronchial tone in normal Ss and in Ss suffering from obstructive bronchial disorders such as bronchial asthma. In addition, augmented sensory feedback of R_T can be utilized in investigations of S's ability to attain voluntary control of R_T .

DESCRIPTORS: Instrumentation, Total respiratory resistance, Augmented sensory feedback. (R. W. Levenson)

The psychophysiological investigation of bronchial asthma has long been complicated by problems inherent in the selection and application of an appropriate measurement technique. The physical alterations accompanying asthma are generally agreed to involve narrowing of the bronchial lumen by smooth muscle spasm, edema of the bronchial mucosa, and hypersecretion (Sherman, 1968). These changes all produce increases in the resistance of the airways to air flow and may lead to the labored breathing which is characteristic of asthma episodes.

Of considerable interest has been the development of a method for measuring the bronchial changes in asthma, which is sufficiently sensitive to assess subclinical variations in response to precipitating stimuli. For a long time, the accurate assessment of airway resistance required either the use of

esophageal balloons or the whole body plethysmograph (Dubois, Botelho, & Comroe, 1956). These techniques involve the use of elaborate equipment and skilled technicians, and they entail considerable disruption of the subject's environment. As a compromise, many psychophysiological investigations of asthma have utilized relatively insensitive measures of ventilatory flow and volume. Although the latter have come under considerable criticism (Stein, 1962), they continue to be used.

An alternative to the body plethysmograph which allows for the determination of total respiratory resistance (R_T) during normal breathing makes use of the forced oscillation technique (Dubois, Brody, Lewis, & Burgess, 1956; Mead, 1960). Briefly, this technique treats the airways as analogous to an electrical circuit with properties of current (air flow), voltage (pressure), and resistance (resistance). By imposing a low frequency pulsation below the resonant frequency at a known pressure to the airway system (i.e., at the mouth), and determining the air flow produced by that pressure, the resistance of the total

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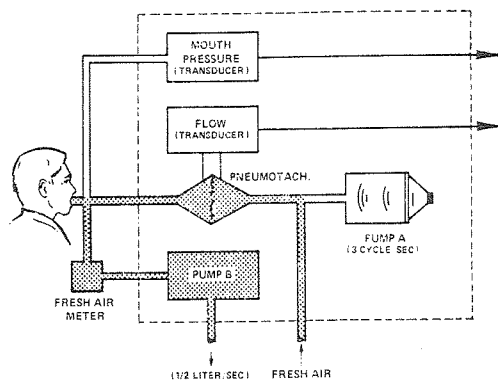


Fig. 1. Block diagram of Respiratory Resistance Unit (reproduced with permission of Lexington Instruments, Waltham, Massachusetts).

respiratory system can be determined by the formula:

$$\text{Resistance} = \frac{\text{Pressure}}{\text{Flow}}$$

Descriptions of forced oscillatory devices have been published by several authors (Grimby, Takishima, Graham, Macklem, & Mead, 1968; Goldman, Knudson, Mead, Peterson, Schwaber, & Wohl, 1970; and Hyatt, Zimmerman, Peters, & Sullivan, 1970). A commercial version manufactured by Lexington Instruments (Waltham, Mass.) is called the Respiratory Resistance Unit (RRU).

Forced oscillation devices allow continuous monitoring of the imposed pressure oscillation and the resultant flow. A system for quantifying this output must provide for: (1) Separation of the imposed pressure and flow from the *S*'s respiratory flow. (2) Determination of the amplitude of the imposed pressure and flow. (3) Determination of the proper time during the *S*'s respiratory cycle to initiate the measurement of R_T . (4) Criteria for discarding spurious readings caused by activity such as swallowing, coughing, yawning, and gross motor movement.

Hyatt et al. (1970) have described such a system using standard electronic circuitry. The present paper describes a technique using a digital computer in conjunction with the RRU. In addition, an extension of the system capability to provide the *S* with rapid information (biofeedback) of his R_T will be presented.

Method

Equipment

A Lexington Instruments RRU (Fig. 1), a Grass Model 7 polygraph, and a Hewlett Packard 2114A digital computer with 8K of memory form the nucleus of the system. Three signals from the RRU are connected to separate polygraph channels (Fig. 2):

(1) *Flow*. The output from the RRU's flow transducer is a composite signal consisting of the flow produced by the 3 Hz forced oscillation superimposed on the flow produced by the *S*'s breathing. This signal is connected to a wide range AC preamplifier with its time constant set at .015 sec, effectively filtering the breathing flow, leaving only the forced oscillatory flow.

(2) *Pressure*. The output from the RRU's pressure transducer is connected to a second wide range AC preamplifier with its time constant set at .015 sec.

(3) *Inspiration-Expiration*. The output from the inspiration detection circuitry in the RRU is connected to a low level DC preamplifier and is DC coupled. This circuit produces a negative voltage during inspiration and a positive voltage during expiration.

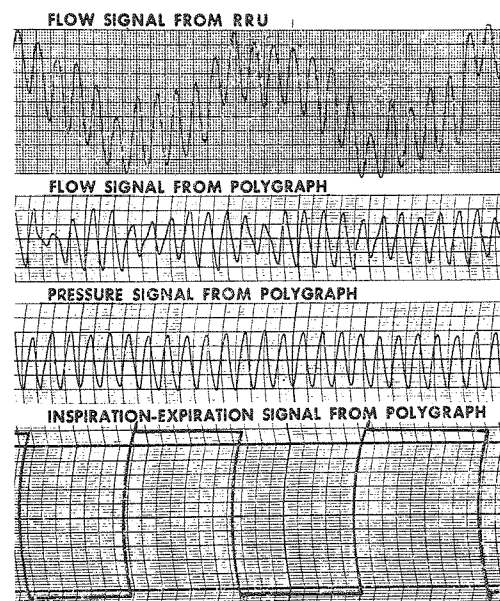


Fig. 2. Representative signals: (1) Flow signal displayed on RRU's recorder; (2) Flow signal after filtering by polygraph; (3) Pressure signal after filtering by polygraph; (4) Inspiration-expiration signal displayed on polygraph.

The output of each polygraph channel is connected to an input channel of the computer's model 5610 multiplexed analog to digital converter. A dual chambered digital display device capable of lighting digits between "1" and "9" in either chamber is operated under program control by means of the computer's external switching relays. Fig. 3 illustrates the complete system.

Calibration

A reliable procedure for calibrating the RRU-polygraph-computer network is crucial. Calibration of the RRU follows the procedure developed by Lexington Instruments and functions to establish the following relationship between flow and pressure and the amount of pen excursion on the RRU's built-in strip chart recorder:

I. FLOW 0.5 LPS = 1 cm of pen excursion.

II. PRESSURE 1.0 cm H₂O

= 1 cm of pen excursion.

Following this internal calibration of the RRU, the mouthpiece is placed over a special passive resistance tube. Servo circuitry in the RRU corrects the pressure of the imposed oscillations to a value of 2 cm H₂O at the start of each inspiration. During this stage of the network calibration, inspiration is simulated by periodically closing a pushbutton switch until the pressure (monitored on the RRU's pressure meter) stabilizes at the nominal 2 cm H₂O. The strip chart recorder is activated and brief samples of the exact flow and pressure are taken.

The calibration is completed by activating a special calibration section of the computer program which samples the flow and pressure analog signals and writes their amplitudes in volts. The sensitivity of the

polygraph amplifiers is adjusted until the computer is printing out the appropriate voltages for the flow and pressure samples as indicated on the RRU's strip chart recorder. The appropriate voltages are determined from the amplitude of the pen excursions such that 1.0 cm pen excursion (for either flow or pressure) = 0.5 V. This relationship when combined with those of Formulae I and II establishes the overall relationship between flow and pressure; pen excursion on the RRU's recorder; and the amplitude of these signals as sampled at the output of the polygraph by the computer, as follows:

III. FLOW 0.5 LPS

= 1.0 cm pen excursion = 0.5 V.

IV. PRESSURE 1.0 cm H₂O

= 1.0 cm pen excursion = 0.5 V.

The full calibration including the internal calibration of the RRU can be accomplished in approximately 15 min.

Computer Program

The computer program is written in the Hewlett Packard version of American Standard basic Fortran. It will be described functionally.

(1) *Amplitude Sampling of Flow and Pressure Signals.* The sampling procedure for the flow and pressure analog inputs forms the basis of the entire calibration, measurement, and feedback procedure. The flow and pressure signals (in the form of 3 Hz sine waves) are sampled simultaneously for a period of 500 msec, thus ensuring that at least one oscillation has occurred. Variables for minimum and maximum voltages are created for flow and pressure and the initial voltages are placed in these variables. During the 500 msec period, subse-

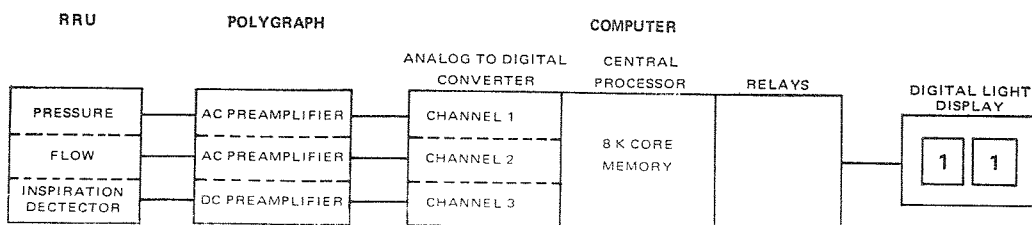


Fig. 3. Block diagram of entire system consisting of RRU, polygraphy, computer, and light display.

quent voltage readings are compared to the current minimum and maximum and updated if appropriate. At the end of the period the absolute differences between the minimum and maximum voltages for flow and pressure are calculated. This yields the amplitudes of the flow and pressure signals in V which can then be converted to LPS and cm H₂O by Formulae III and IV, respectively.

(2) *Calculation of R_T .* R_T is computed at the start of each inspiration. The inspiration detector voltage is monitored until it becomes negative marking the start of inspiration. At this point, a 500 msec sample of the pressure and flow signals is initiated; pressure and flow amplitudes are converted to cm H₂O and LPS; and respiratory resistance is calculated by the formula:

$$R_T = \frac{\text{Pressure (cm H}_2\text{O)}^1}{\text{Flow (LPS)}}$$

(3) *Inspiration and Expiration Durations and Ratios.* The durations of the inspiratory and expiratory phases of respiration are continually determined by monitoring the state of the inspiration detection channel. Timing is accomplished via crystal-based computer clocks, one being used to time the length of inspiration and a second to time expiration. After a predetermined number of breaths, the means and standard deviations of the lengths of inspiration and expiration are determined, as well as the inspiration-expiration ratio and the average respiratory cycle length.

(4) *Detection of Artifacts.* Any automated technique for quantifying physiological data is obviously vulnerable to false readings produced by artifactual occurrences. The measurement of R_T is vulnerable to any action which artificially alters the state of the airways. *S*'s body movement,

¹The major component of the resistance determined in this manner is flow resistance. Components of inertial and elastic resistances "cancel out" as they are essentially equal at the points of peak flow (i.e., of zero volume acceleration) represented by the minimum and maximum voltages on the oscillatory flow signal (Goldman et al., 1970). Calculation of resistance during inspiration may eliminate several potential artifacts which are present during expiration in normal *S*s and *S*s with obstructive lung disease (Goldman et al., 1970).

hiccups, coughs, and yawns all can play havoc with the forced oscillatory readings. Sensitivity to these artifacts is built into the computer program in two ways. First, no measurement of R_T is attempted if the oscillatory pressure deviates more than 0.3 cm H₂O from the nominal 2 cm H₂O. As mentioned earlier, the RRU has servo circuitry which constantly corrects pressure deviations from 2 cm H₂O. Fortunately, most of the foregoing factors leading to false readings also produce a sharp deviation of the imposed pressure from the 2 cm H₂O level. Thus, by initiating measures only when the pressure is close to this value, resistance determination may be delayed for several breaths following the artifactual activity until the pressure level is reestablished. The second protection is provided by setting a cut-off value of a number of standard deviation units from the individual's mean resistance and rejecting all readings outside of this "confidence interval." This control procedure admittedly runs the risk of discarding legitimate albeit deviant readings. The program allows the experimenter to establish these limits and keeps a record of the number of readings which are discarded during a given trial. Under normal conditions few deviant readings are recorded.

The foregoing procedure provides a straightforward approach to computer quantification of the RRU's output. An estimate of its reliability has been obtained by initiating measures of R_T on a passive resistance plug (resistance = 4.0 cm H₂O/LPS). The standard deviation of 15 successive readings is typically less than 0.05 cm H₂O/LPS.

The addition of a methodology for providing the *S* with rapid feedback of his R_T reflects an interest of our research group in the voluntary control of respiratory resistance. In the following section the feedback system currently in use is described.

Feedback

A viable feedback system must take into account interindividual and intraindividual variability, both in the normal state and during feedback training. Accordingly, feedback is always presented relative to a recently determined baseline mean and

standard deviation R_T . After a baseline period (usually 15 breaths), criteria are established for illuminating one of seven digits constituting the feedback. At the start of inspiration the computer determines R_T as outlined above and compares this to the baseline mean R_T and standard deviation. If R_T is within ± 0.5 standard deviations from the baseline mean, the digit "4" is illuminated. Successive 1.0 standard deviation bands are established for higher digits (which are associated with higher resistances) and lower digits (which are associated with lower resistances). In this way a subject on any trial would normally receive mostly "4"'s. When trying to control his resistance he employs various strategies and if he is successful is "rewarded" by lighting either higher or lower numbers depending on the direction of change he is attempting. At the end of each baseline and feedback period the program provides a written record of: (1) Respiratory resistance mean and standard deviation; (2) duration of inspiration and expiration means and standard deviations; (3) mean inspiration-expiration ratio; and (4) mean length of respiratory cycle; in addition, following feedback periods, (5) number of times each feedback digit was illuminated; and (6) R_T means for successive groups of 3 breaths.

Discussion and Summary

Since the role of psychological precipitants in symptom production in bronchial asthma is well established for a subset of the asthmatic population, the syndrome is of great interest to the psychophysicologist. Measures of bronchial constriction enable the study of subclinical changes in the relevant physical system in response to controlled stimuli. With the introduction of the forced oscillation technique, the measurement of bronchial constriction has been greatly simplified. The present paper has attempted to outline a method for integrat-

ing such a device into a computer-based laboratory. An earlier paper by Hyatt et al. (1970) provides an alternative method for a polygraph laboratory without a computer. Since the solution of the technical problems in either case is not unusually difficult, the way is open for using these methodologies to study the psychophysiology of bronchial asthma. In addition, the viability of external feedback of respiratory resistance using a laboratory computer is greatly facilitated by the forced oscillation technique which allows a continuous and nondisruptive determination of this variable. Voluntary control of symptom-related visceral responses as well as the precise measurement of physiological responses to psychological stimuli offers interesting possibilities in the study and treatment of bronchial asthma.

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