

RADIOTELEMETRIC CARDIORESPIRATORY DETERMINATIONS DURING SUBMAXIMAL DYNAMIC EXERCISE

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Summary Under normal conditions, healthy people at submaximal exercise show a close correlation between work load and cardiac output (i.e. oxygen uptake versus heart rate, respectively). Subjects with chronic bronchospastic disease respond to specific bronchodilators (e.g. isoproterenol) with increases in heart rate -- even without exercise. New bronchodilators (salbutamol) which do not exert such an influence on the heart rate are being studied for their effect on "exercise induced asthma."

Measurements of airway resistance (R_A) and thoracic gas volume (V_{tg}) during dynamic exercise (treadmill) pose complex instrumentation problems. The radiotelemetric determinations of specific airway conductance (G_A/V_{tg} where $G_A = 1/R_A$) now appear practicable. The acquisition of such data in conjunction with other radiotelemetered measurements (heart rate from R-R interval) indicate that patients with chronic bronchospastic disease, when treated with bronchodilators, may tolerate physical exercise more safely.

Introduction Cardiorespiratory parameters which are influenced by training and have been measured at rest and during submaximal work have been reviewed by Astrand.¹ During submaximal treadmill exercise, Belke² has shown that there is a linear relationship amongst systolic blood pressure, respiratory frequency, carbon dioxide output, oxygen consumption and pulse rate. Since oxygen consumption and heart rate show a close correlation and are indicative of work load and cardiac output, respectively, these readily measurable parameters are most commonly monitored during treadmill tests. Work capacity is calculable, and heart rate is easily monitored by radiotelemetry of the electrocardiographic signals. The measurement of airway resistance has not yet been possible during dynamic exercise and this is one of the parameters that provides the needed information for the evaluation of bronchodilator therapy of patients with pulmonary disease.

Methodology To date, whole body plethysmography has been the technique for the determinations of airway resistance (R_A) and thoracic gas volume (V_{tg}). To acquire these data, the subject must be placed within a sealed box (static condition). This transition, although only necessitating a delay of 15 seconds under optimal conditions, does not permit of other simultaneous measurements. Furthermore, such data no longer corresponds to exercise (i.e. is not on-line); and, if denoted as “end-exercise”, is not so, but really the first datum point in measurements of the recovery phase. It has been shown in normals that the pattern of recovery from exercise, determined by pulse rate alone, is a useful index of physical fitness for hard muscular work.³

In a report of measurements of specific airway conductance during exercise, Kagawa and Kerr⁴ incorporated a bicycle ergometer within the “body-box”. Unfortunately, the technique required cessation of pedaling activity and stoppage of the ergometer “to prevent vibration from interfering with the plethysmographic measurements.” This, while decreasing the transition period, is still not “on-line”. Moreover the data was derived using normal subjects.

Subjects with chronic bronchospastic disease who have limitations, whether pathologic and/or psychologic, in their ability to perform strenuous work, require special consideration. Acute asthmatic attacks, triggered by exercise, may preclude a standardized time sequence of measurements. Thus the desirability of continuous on-line measurement is evident to permit a flexible schedule. Such a technique would not only ensure better patient tolerance but also improve medical care by providing a greater margin of safety.

In the evaluation of bronchodilator agents to determine their efficacy in extending tolerance of asthmatics to physical exercise, Steen et al⁵ noted the necessity for on-line measurements of airway resistance. One of ten patients in a recent study⁶ went into an acute asthmatic attack whilst exercising on the treadmill. This occurred at a time less than that which the patient had previously tolerated for the fixed work capacity levels to which all were subjected. Recovery was so slow that no further data could be obtained on that subject who later required individualized therapy.

Radiotelemetric monitoring of the electrocardiographic signals of both normal and asthmatic subjects during exercise presented the expected motion-induced artifacts. Since the pulse rate, as determined from the number of R-R intervals, was of prime consideration rather than waveform abnormalities of myocardial potentials, adequate rate information was obtained following experimental optimization of electrode placement in this study. Contrary to expected results, determinations of specific airway conductance (measured off-line by whole body plethysmography) showed an increase immediately following strenuous exercise (treadmill).

This phenomenon, surprisingly enough, was also elicited in non-medicated asthmatics whose exercise induced asthma was the anticipated result (i.e. a decreased specific airway conductance).⁶ To eliminate the tachycardic effects (even at rest) of a commonly used bronchodilator, isoproterenol, a new betaadrenergic receptor_stimulating drug, salbutamol, was used in a subsequent study,⁷ because it was shown to have negligible effects on heart rate even in large doses.⁸ Similar findings for specific airway conductance were obtained in asthmatics who received both salbutamol and placebo. Of note, was the fact that marked differences occurred at the immediate post-exercise time period (15 seconds) as compared to more traditional ones measured at 5-minute post-exercise intervals. Specifically, the response to placebo was shown as an increase in G_A/V_{tg} immediately post-exercise with subsequent decrease in the recovery phase prior to its return to the pre-exercise range; whereas, no such immediate post-exercise increase was seen following active drug therapy. This emphasizes the need for continuous on-line data acquisition of this important respiratory parameter, for the interpretation of drug effects, if any, must be properly placed within the framework bounded by respiratory pathology, pharmacologic medication and timing, as well as the physical activities of the patient.

New Technique An approach to acquire such on-line data requires the elimination of the body-box which serves only to quantitate the volume changes during respiratory activity in a sequence of flow and no-flow cycles. These volume changes are not equal to the volumes inspired in that compression and expansion of the inspired gases takes place in the elastic container which is the lung. These changes, sensed as box pressure changes ($PV = \text{constant}$; Boyle's Law), serve as the common denominator to relate flow (when there is a normal pressure gradient) and mouth pressure (when there is no flow).⁹ The bracketed ratios in equations 1, 2, and 3 are traditionally determined from the tangents of the angles which Lissajous patterns form with the horizontal, when the appropriate signals are cross plotted oscilloscopically; box pressure is the horizontal variable.¹⁰ (See photograph number 1.) The relationship between pressure and flow, albeit measured during sequential cycles, determines the airway resistance ($R_A = 1/G_A$).

$$R_A = K_1 \frac{\left[\frac{\Delta(\text{mouth pressure})}{\Delta(\text{box pressure})} \right]}{\left[\frac{\Delta(\text{flow})}{\Delta(\text{box pressure})} \right]} \quad \text{equation (1)}$$

The volume of gas in the lungs ($V_{t,,}$) may be calculated from the product of the known pressure at the moment of respiratory reversal (atmospheric pressure) times the ratio of the body volume displacement (due to thoraco-abdominal excursion) to the pressure change which caused the displacement (no-flow).

$$V_{tg} = K_2 \left[\frac{\Delta (\text{box pressure})}{\Delta (\text{mouth pressure})} \right] \quad \text{equation (2)}$$

From these parameters specific airway conductance is calculable as G_A/V_{tg} .

In performing the two measurements, the no-flow condition imposed upon the subject necessitates the insertion of a mechanical occlusive device (solenoid operated shutter). To obviate this constraint, one of the authors (R. Crane) has shown that the determination of G_A/V_{tg} does not require the no-flow condition. Thus, the occlusive device (and the closed shutter relationship derived therefrom) is superfluous, when only the relationship G_A/V_{tg} is of interest.

$$\frac{G_A}{V_{tg}} = \frac{1}{K_1 K_2} \left[\frac{\Delta (\text{box pressure})}{\Delta (\text{flow})} \right] \quad \text{equation (3)}$$

This greatly reduces the instrumentation problem to one of replacing the box as a measure of thoraco-abdominal volumetric changes.

Several methods of obtaining the volume of the thorax and abdomen have been described. Strain gauges made with silastic tubing, filled with mercury, have been used to encircle both these portions of the human anatomy. These transducers, with appropriate circuitry, provide signals which vary during respiration. Two signals from thoracic and abdominal dimensional changes were compared with other known measurements for total volume from which coefficients were derived to yield an empirical formula.¹¹ Impedance plethysmography (ZPG) is another technique in which a portion of the body is a component of an alternating current Wheatstone bridge.¹² This concept is dependent upon the variation of the electrical impedance caused by the alteration of the body composition during the respiratory cycle. Placement of the electrodes for the insertion of the appropriate carrier frequency as well as for detection of the resultant impedance change is critical. Pathology may shift the burden toward abdominal breathing. Furthermore, in the asthmatic, shifts between abdominal and thoracic components are common and vary depending on many factors other than exercise. One example is whether the measurement of airway resistance is during spontaneous respiratory activity or requires that short rapid breathing maneuvers (panting) be performed. Another observation is that such shifts are seen in subjects whose psychiatric states vary abnormally.¹¹

By utilizing the impedance plethysmographic technique (ZPG) it is often possible to greatly simplify the electrode placement and the electronics of the telemetry system. One pair of electrodes is sufficient to provide both the ZPG and ECG information; the electrodes are placed at mid axillary and mid nipple line, and are connected to two separate circuits in parallel. In one they provide the electrical potential of the myocardium directly to an appropriate ECG preamplifier. In the other, they complete the

four arm a-c operated Wheatstone bridge. The ZPG excitation and detection circuitry convert the carrier signal to a slowly varying d-c proportional to respiratory filling. Thus the subject will be minimally encumbered in the optimal case wherein only thoracic, rather than a combination of thoracic and abdominal breathing occurs, and where muscle artifact considerations allow a trans-thoracic pickup for ECG.

Automation of the individual variables, RA and Vtg, has already been performed.^{13,14} The simplification offered by the shutterless technique described herein reduces the hitherto high economic barrier to the application of computer methodology in whole body plethysmography.

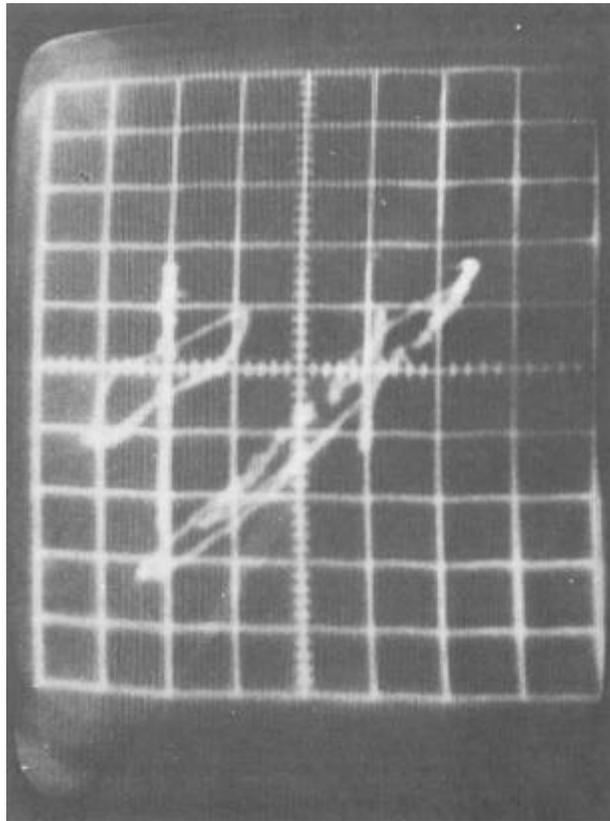
The elimination of the body-box should so simplify the technique that many more studies will be undertaken to monitor this significant pulmonary index (G_A/V_{tg}). Both mercury and impedance plethysmographic methods are amenable to radiotelemetric transmission over the FM-FM IRIG compatible multiplex system. The use of IRIG channel assignments and multiplexing standards in commercially available miniature telemetry systems permits excellent noise-free transmission over practical hospital laboratory environments, with a minimum weight transmitter module worn by the exercising subject. (See photograph number 2.) The use of the 215 to 260 MHz band, rather than broadcast F-M (88 to 108 MHz) has eliminated the competition for clear channel space observed so often in metropolitan centers.

A direct read-out (DVM) of the specific airway conductance is mandatory if true on-line data is to result. This type of monitoring provides the clinician with information for optimizing patient care.

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Several loops during panting are stored on the oscilloscope display. The smaller loop in the upper half of the screen depicts the relationship of airflow to change in box pressure when the subject panted through the open apparatus. The mouth shutter was then closed, and the lower loops show change in mouth pressure versus change in box pressure when the subject continued to pant. The upper beam moved along a horizontal plane during the latter maneuver, indicating that airflow was zero during panting efforts against a closed shutter.



Two channel FM-FM telemetry transmitter for ECG and ZPG on separate IRIG sub-carriers, and one transmitting carrier in the 215-260 MHz band. (Courtesy of Bio-Sentry Telemetry, Inc., Torrance, California.)