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## AN IMPEDANCE RESPIROMETER

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FOREWORD

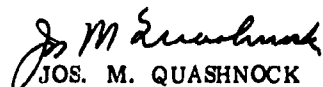
This study was performed in the Medical Electronics and Psychophysiological Stress Branches, Multi-Environment Division, Biophysics Laboratory, 6570th Aerospace Medical Research Laboratories, Aerospace Medical Division, between August of 1961 and August of 1962. The work was performed under Project No. 7222, "Biophysics of Flight," Tasks No. 722203, "Bioinstrumentation," and No. 722201, "Psychophysiology of Flight." Acknowledgment is made to Mr. M.A. McLennan, Mr. E.G. Correll, Mr. J.H. Lovin, Mr. A. Lombardo, and Captain G. Potor, USAF, MC, for their assistance in conducting these experiments.

#### ABSTRACT

When a low-intensity, high-frequency (20-60 kc) carrier signal is applied to a human subject between axillary electrodes, a change in impedance can be measured between the electrodes. This change in impedance closely parallels the simultaneous changes in the volume of respired air. The design and circuitry of an impedance respirometer are presented. Simultaneous tracings from this respirometer and a wedge spirometer were recorded from ten subjects during quiet sitting, standing, walking, and running in place through the physiological range of respiratory rate (8-40 breaths/min) and volume (2-4 liters). The output of the impedance respirometer correlated well with the output of the wedge spirometer in the quiet, seated subject. The problems of electrode configuration, body type, and electrode artifact are discussed. This system is a reliable and unencumbering method of monitoring respiratory rate and, potentially, respiratory volume. However, its use is severely limited by baseline shifts and motion artifact due to changes in electrode impedance.

#### PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

  
JOS. M. QUASHNOCK  
Colonel, USAF, MC  
Chief, Biophysics Laboratory

## AN IMPEDANCE RESPIROMETER

### INTRODUCTION

Impedance plethysmography is a well established electronic technique for the measurement of volume change and flow in biological systems (ref. 6). In 1935 Atzler noted respiratory waves in recordings of chest-to-back impedance changes related to cardiac activity (ref. 1). In 1946 Holzer, Polzer, and Marko worked to eliminate the respiratory artifact from their rheocardiogram (ref. 4). Impedance change across the chest has been established as a useful analog of respiratory rate and possibly tidal volume (refs. 2, 3).

In a number of inaccessible laboratory and environmental situations the standard clinical spiograph or pneumotachygraph cannot be used to monitor respiratory rates and volumes in human subjects due to limitations of space or equipment. Many reliable and unencumbering devices are available to monitor respiration in such situations. A common device incorporates an elastic belt with some type of attached strain gauge which records expansion of the thoracic cage. Additional work of respiration is required to expand the belt, the belt may become uncomfortable, the breathing pattern may become unconsciously altered to avoid expanding the belt, and the signal may be lost. Another simple method of recording respiratory rate measures the resistance change in a small thermistor as the subject's breath flows across it. The principal problem is mounting the thermistor. Using a nose clip ignores the fact that one often breathes through the mouth. Attempts have been made to mount the thermistor in a helmet in such a position that it is near both the nose and the mouth, but again the signal may be lost if the subject turns his head.

There is an urgent need in the field of environmental physiology, particularly in aerospace research, for a simple, reliable, unencumbering respirometer. Recent publications (refs. 2, 3) have described impedance devices suitable for respirometry but no significant amount of data generated by these devices has been reported. We need information regarding the reliability, stability, sensitivity, frequency and amplitude response characteristics, and phase shifts of the output of an impedance respirometer. Appropriate calibration is obviously mandatory for the routine use of such a device. The physiological factors responsible for the changes in impedance measured across the chest are also unknown. In this report we present the design and circuitry of an impedance respirometer and a consideration of problems encountered in its use in the collection of physiological data.

In all of our designs we have tried to provide a minimum power consumption (only transistors were used), smallest possible size and weight, and the least possible encumbrance for the subject. The most practical circuit we have at the present time is shown in figure 1. The electrodes are connected directly to the secondary winding of the oscillator transformer. Due to the changing load on the oscillator, the respiratory signal appears on the rectified portion of the oscillator output. By proper selection of the transformer ratio, adjustment of the oscillator bias, and the use of the voltage doubler form of rectification, we were able to reduce the direct-current amplification necessary. This circuit has been used successfully in both telemetry and direct-wire setups.

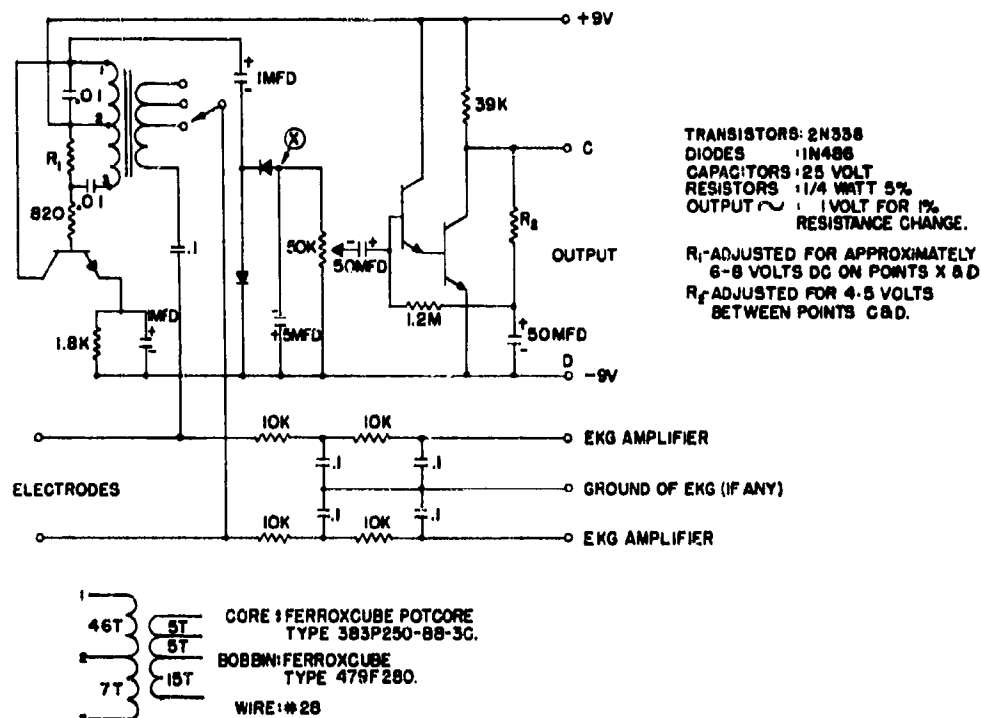


Figure 1. Circuit Diagram of the Impedance Respirometer



## METHOD

In an initial study 17 seated normal male subjects were studied by simultaneous recordings from the impedance respirometer and a servospirometer (Custom Engineering and Development\*, Model 350) written out on a two-channel penwriter (Brush Instruments†). The signals from the spirometer and the impedance device were fed into an analog computer (Donner‡, Model 30) and the computed voltage difference between the two signals recorded on a separate penwriter (Brush Instruments). Subjects breathed through a mouthpiece from an oxygen-loaded closed system containing soda-lime for carbon dioxide removal.

In a subsequent study ten (different) normal male subjects were used. The simultaneous outputs of a wedge spirometer (Custom Engineering and Development, Model 170) and the impedance respirometer were recorded on a multiple-channel oscillograph (Offner\*\* Dynagraph, Type R). Recordings were made of minimal and maximal rates and amplitudes of respiration while subjects were sitting, standing, walking, and running. A variety of electrode types and positions were studied. Because of variations in electrode impedance, constant adjustment of the respirometer potentiometer was necessary to keep the respirometer at the same gain as the wedge spirometer. The equality of the gains was judged by eye from the tracings. The impedance signal was therefore both uncalibrated and not at a constant gain. Therefore, we did not obtain quantitative data relating the two recorded wave forms.

## RESULTS

The computer output in the initial study demonstrated that in quiet, seated subjects the respirometer output voltage was greater—but not by more than 5%—than the spirometer output after both were initially adjusted to the same gain through the physiological range of respiratory rates (8-40 breaths/min) and volumes (1-4 liters).

In the second group of subjects the problems of electrode type and position were studied. The recordings from a representative subject are shown in figures 2 through 5. The upper tracing of each pair is from the impedance respirometer and the lower tracing from the wedge spirometer. The tracings are read from right to left, and the paper speed is 2.5 mm per second. The gain is constant in all of these tracings. A 1-liter calibration is given on the wedge spirometer tracing. There is a good apparent correlation between the simultaneous wave forms generated by the two instruments although this relationship is not quantitated in this study. Good correlation of both the amplitude response (a) and the frequency response (b) in the ranges studied is demonstrated (figure 2). There is no obvious phase shift on these tracings.

Figure 3 demonstrates the effect of standing (c), walking in place (d), and running in place (e) on the impedance trace. An increasing degree of artifact with increasing subject motion is apparent. Figure 4 demonstrates loss of the respiratory signal from the impedance device due both to change in the base line and to motion artifact. Figure 5 demonstrates two Valsalva maneuvers (forced expiration against the closed glottis). The flat plateau of the spirometer tracing indicates a constant pulmonary air volume, assuming intrapulmonic pressure to be constant during the maneuver and disregarding consideration of volume change due to gaseous diffusion. However, the impedance trace is not flat but rather has a small pulse both at the onset and the end of the plateau. This indicates that unknown factors other than the volume of respired air do alter transthoracic impedance changes related to respiration.

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\* Custom Engineering and Development Co., 2647-49 Locust St., St. Louis 3, Missouri

† Brush Instruments Div., Clevite Corp., 37th and Perkins, Cleveland 14, Ohio

‡ Donner Scientific Co., 888 Galindo St., Concord, California

\*\* Offner Div., Beckman Instruments, Inc., 3900 River Rd., Schiller Park, Illinois

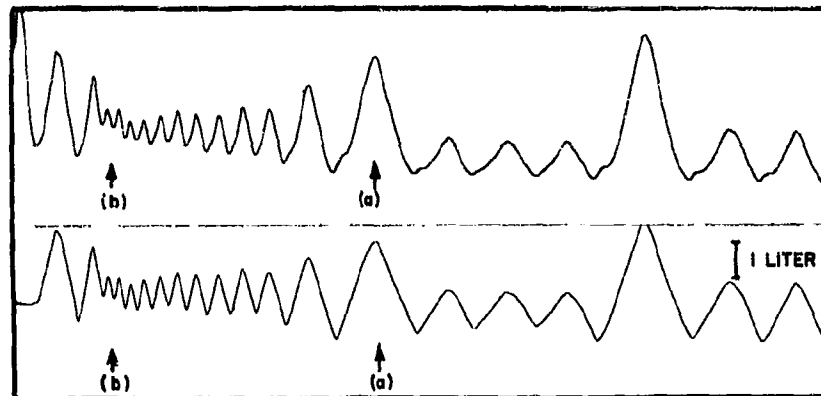


Figure 2. Tracings from a Representative Subject Showing a Maximal Amplitude Response at (a) and a Rate Response at (b)

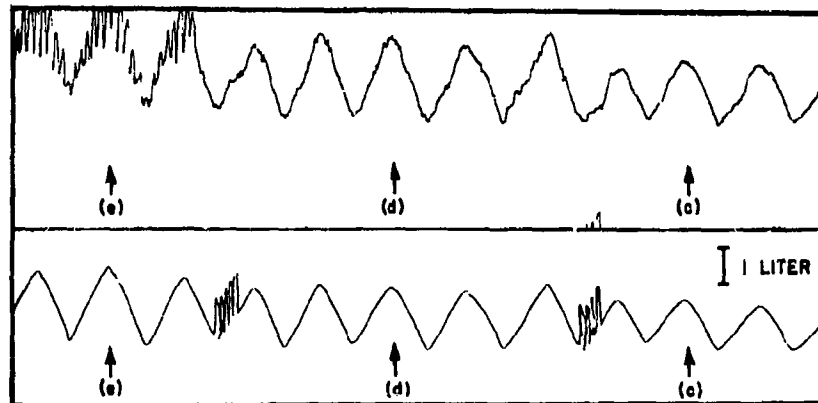


Figure 3. Tracings from a Representative Subject Recorded during Standing (c), Walking (d), and Running in Place (e). Moderate Artifact Is Seen at (d) and (e).

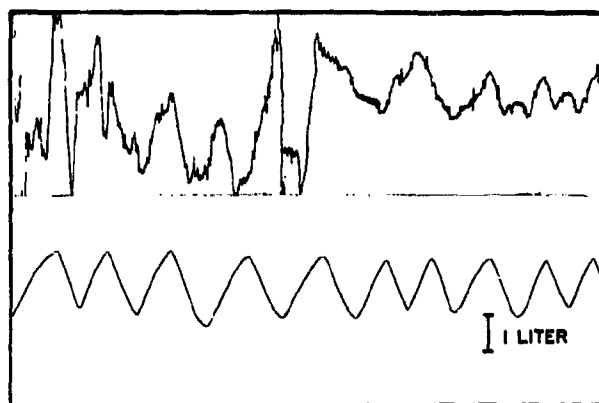


Figure 4. Representation of Severe Base Line and Motion Artifact during Running

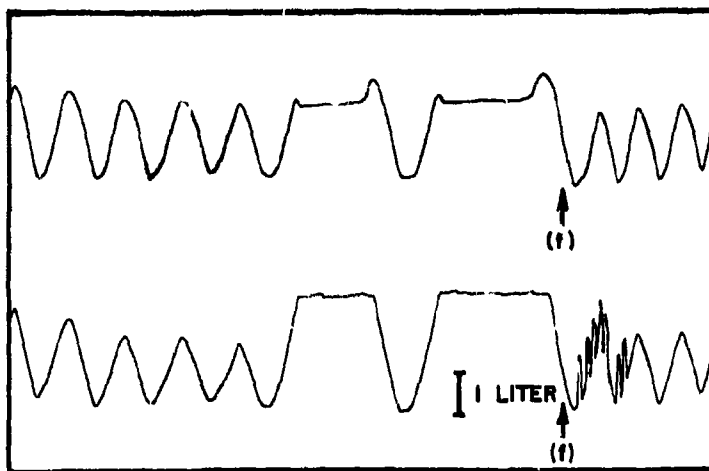


Figure 5. Representation of Two Consecutive Valsalva Maneuvers

### Electrodes

As in many bioelectronic systems the most unstable link in the impedance respirometer is the junction between the instrument and the organism—in this case, electrodes. The many problems of surface biological electrodes have been reviewed recently and are not discussed here (ref. 7).

A variety of electrode types were tried with the impedance respirometer, including: needles, electrocardiographic and electroencephalographic electrodes, strips of silver cloth, and a commercially available adhesive-backed metal gauze (Telectrode, Telemedics, Inc.\*). The signal recorded from the needle electrodes was extremely weak, unstable, and susceptible to motion artifact. Minimal electrode surface was not determined, but the necessity for some sufficient electrode area to obtain a maximal signal suggests a capacitance component in the recorded impedance change. Clinical electrocardiographic electrodes and silver cloth (1½ by 1½ inches) applied with electrode paste (Itodux, Sanborn†) were satisfactory but very sensitive to motion artifact and drying. The adhesive-backed metal gauze electrode was in all respects the most satisfactory.

A variety of points of electrode attachment were studied. When applied over the sixth intercostal space in the mid or anterior axillary line bilaterally, a useful signal, equal to no less than 1 liter per centimeter on the wedge spirometer trace, was detected in 27 of 27 consecutive subjects. With biaxillary electrodes, the largest signal is obtained in or near the sixth intercostal space and falls off above and below this point. Figure 6 shows the strength of signals obtained in three subjects in the fourth through the eighth intercostal space. This confirms similar observations by Geddes et al. (ref. 2). However, comparable signals were obtained from electrodes at the right sixth intercostal space and at the xiphoid or the midscapular line at the level of the sixth thoracic vertebra.

\* Telemedics, Inc., Vector Manufacturing Co., Inc., Southampton, Pennsylvania

† Sanborn Co., Medical Div., 175 Wyman St., Waltham, Massachusetts

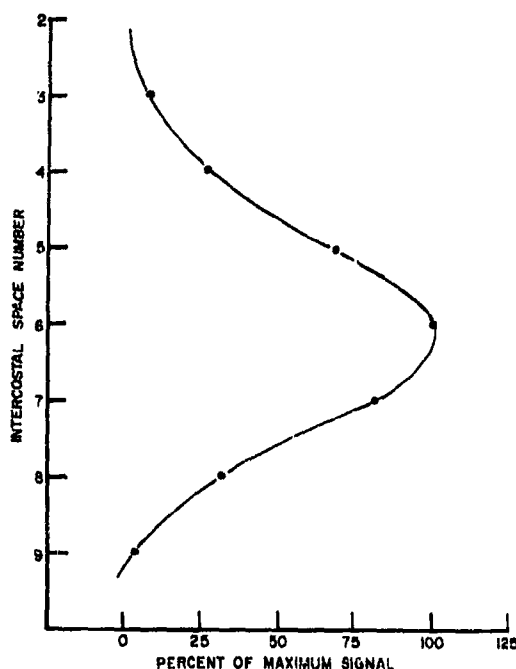


Figure 6. The Impedance Respirometer Signal Strength from Electrodes at the Fourth through the Eighth Intercostal Spaces Bilaterally Plotted as Percent of the Signal from the Sixth Intercostal Space

with an anthropologist's spring-loaded, skin-fold calipers. Thickness varied from 0.45 to 1.30 centimeters. The degree of motion artifact appeared to correlate directly with the skin-fold thickness. The relatively mild motion artifact with running seen in figure 3(e) is from a subject with a skin-fold thickness of 0.50 centimeter while the severe motion artifact seen in figure 4 is from a subject with a skin-fold thickness of 1.20 centimeters.

#### The Biophysics of the Impedance Respirometer

The factors responsible for the change in impedance measured across the chest during respiration remain unknown. Nyboer (ref. 6) has presented impedance plethysmography in terms of resistive changes in body segments viewed as volume conductors. Under certain conditions, as illustrated in figures 2 and 5, the impedance change across the thorax does correlate well with respired air volumes as measured by the spirometer. The roles of respiratory blood volume shifts, tissue tension, and capillary or lymphatic volumes, for example, are unknown. However, it is possible to separate the in-phase and the quadrature components of the impedance change. By shifting the phase  $90^\circ$  in one channel and using the same reference voltage for both phase detectors another channel may be made to measure only the reactive component of transthoracic impedance. A schematic representation of such a quadrature detector is seen in figure 7. Although this work is incomplete, our findings tend to support the observations of Nyboer (ref. 6) that the major impedance change during the respiratory cycle occurs as reactance rather than resistance. This may be due to a reactive component in the electrode coupling or to physiological factors which remain unknown.

The stability of the impedance respirometer is limited by the stability of the resistance at the skin electrode interface. The observed respiratory change in impedance is of the magnitude of 1 ohm on a constant level of 100 to 200 ohms (ref. 3). Any factor, such as motion or pressure, which alters the resistance at the electrode by as little as from 1 to 2 ohms will produce an artifact in the tracing. It is readily apparent that the degree of artifact increases with increasing subject activity from quiet sitting (see figure 2) through standing and walking to running in place (see figure 3). An example of loss of the signal due to motion artifact during running is seen in figure 4. A more stable electrode system must be developed before the impedance respirometer can be presumed to give a respiratory volume analog signal, especially in moving subjects.

#### The Role of Body Type

Subjects were not classified according to height, weight, or somatotype, but no extremes of body build were studied. An impedance signal equal to no less than 1 liter per centimeter on the wedge spirometer was obtained from all subjects. Although the observation was not quantitated, it was evident that at equal gain a smaller signal was obtained from the heavier subjects and that the largest signals were from subjects with thin chest walls. Skin-fold thickness at the sixth intercostal space in the mid-axillary line in eight subjects was measured

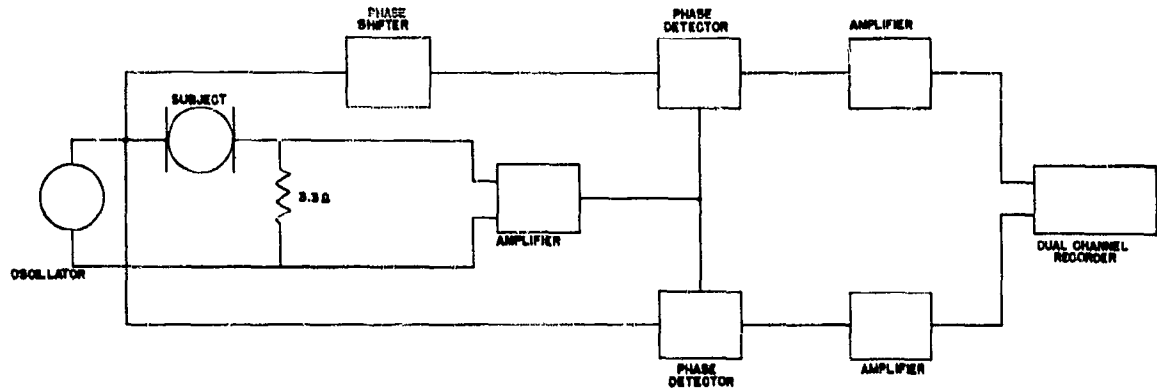


Figure 7. The Quadrature Detector for Impedance Measurement

## CONCLUSIONS

These studies have demonstrated a number of useful advantages of the impedance respirometer:

- a. It provides a simple and reliable means of recording respiratory rate.
- b. Its two lightweight electrodes provide a minimum of encumbrance to the subject.
- c. The same pair of electrodes may be used to obtain an electrocardiogram.
- d. Once suitable electrode stability and instrument calibration are achieved, trans-thoracic impedance change may be used as an analog of respiratory volume as well as rate.

The problem areas and disadvantages associated with this impedance respirometer include:

- a. Base lineshifts due to changes in electrode impedance
- b. Subject movement artifact
- c. Poor signal quality from some subjects, especially the obese

Much work remains to be done in the areas of electrode design, instrument calibration, and circuit improvement. The physiological mechanisms responsible for the respiratory impedance change itself also should be determined.

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| <p>Aerospace Medical Division,<br/>6570th Aerospace Medical Research<br/>Laboratories, Wright-Patterson AFB, Ohio.<br/>Rpt. No. AMRL-TDR-63-45. AN IMPEDANCE<br/>RESPIROMETER. Final report, Jun 63, iii + 8 pp.<br/>incl. illus., 7 refs.      Unclassified report</p> <p>When a low-intensity, high-frequency (20-60 kc) carrier signal is applied to a human subject between biaxillary electrodes, a change in impedance can be measured between the electrodes. This change in impedance closely parallels the simultaneous changes in the volume of respired air. The design and circuitry of an impedance respirometer are presented. Simultaneous tracings from this respirometer and a wedge spirometer were recorded from ten subjects during quiet</p> <p>( over )</p> | <p>UNCLASSIFIED</p> <p>1. Respirometer<br/>2. Impedance<br/>3. Electrodes<br/>I. AFSC Project 7222, Task 722203<br/>II. Biophysics Laboratory<br/>III. McCally, M. Barnard, G.W. Robins, K.E. Marko, A.R.<br/>IV. In DDC collection<br/>V. Avail fr OTS: \$0.50</p> | <p>Aerospace Medical Division,<br/>6570th Aerospace Medical Research<br/>Laboratories, Wright-Patterson AFB, Ohio.<br/>Rpt. No. AMRL-TDR-63-45. AN IMPEDANCE<br/>RESPIROMETER. Final report, Jun 63, iii + 8 pp.<br/>incl. illus., 7 refs.      Unclassified report</p> <p>When a low-intensity, high-frequency (20-60 kc) carrier signal is applied to a human subject between biaxillary electrodes, a change in impedance can be measured between the electrodes. This change in impedance closely parallels the simultaneous changes in the volume of respired air. The design and circuitry of an impedance respirometer are presented. Simultaneous tracings from this respirometer and a wedge spirometer were recorded from ten subjects during quiet</p> <p>( over )</p> | <p>UNCLASSIFIED</p> <p>1. Respirometer<br/>2. Impedance<br/>3. Electrodes<br/>I. AFSC Project 7222, Task 722203<br/>II. Biophysics Laboratory<br/>III. McCally, M. Barnard, G.W. Robins, K.E. Marko, A.R.<br/>IV. In DDC collection<br/>V. Avail fr OTS: \$0.50</p> |
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| <p>Aerospace Medical Division,<br/>6570th Aerospace Medical Research<br/>Laboratories, Wright-Patterson AFB, Ohio.<br/>Rpt. No. AMRL-TDR-63-45. AN IMPEDANCE<br/>RESPIROMETER. Final report, Jun 63, iii + 8 pp.<br/>incl. illus., 7 refs.      Unclassified report</p> <p>When a low-intensity, high-frequency (20-60 kc)<br/>carrier signal is applied to a human subject<br/>between biaxillary electrodes, a change in<br/>impedance can be measured between the elec-<br/>trodes. This change in impedance closely paral-<br/>lels the simultaneous changes in the volume of<br/>respired air. The design and circuitry of an<br/>impedance respirometer are presented. Simul-<br/>taneous tracings from this respirometer and a<br/>wedge spirometer were recorded<br/>from ten subjects during quiet</p> <p>( over )</p> | <p>UNCLASSIFIED</p> <p>1. Respirometer<br/>2. Impedance<br/>3. Electrodes<br/>I. AFSC Project 7222,<br/>Task 722203<br/>II. Biophysics<br/>Laboratory<br/>III. McCally, M.<br/>Barnard, G.W.<br/>Robins, K.E.<br/>Marko, A.R.<br/>IV. In DDC collection<br/>V. Aval fr OTS: \$0.50</p> | <p>Aerospace Medical Division,<br/>6570th Aerospace Medical Research<br/>Laboratories, Wright-Patterson AFB, Ohio.<br/>Rpt. No. AMRL-TDR-63-45. AN IMPEDANCE<br/>RESPIROMETER. Final report, Jun 63, iii + 8 pp.<br/>incl. illus., 7 refs.      Unclassified report</p> <p>When a low-intensity, high-frequency (20-60 kc)<br/>carrier signal is applied to a human subject<br/>between biaxillary electrodes, a change in<br/>impedance can be measured between the elec-<br/>trodes. This change in impedance closely paral-<br/>lels the simultaneous changes in the volume of<br/>respired air. The design and circuitry of an<br/>impedance respirometer are presented. Simul-<br/>taneous tracings from this respirometer and a<br/>wedge spirometer were recorded<br/>from ten subjects during quiet</p> <p>( over )</p> | <p>UNCLASSIFIED</p> <p>1. Respirometer<br/>2. Impedance<br/>3. Electrodes<br/>I. AFSC Project 7222,<br/>Task 722203<br/>II. Biophysics<br/>Laboratory<br/>III. McCally, M.<br/>Barnard, G.W.<br/>Robins, K.E.<br/>Marko, A.R.<br/>IV. In DDC collection<br/>V. Aval fr OTS: \$0.50</p> | <p>UNCLASSIFIED</p> <p>sitting, standing, walking, and<br/>running in place through the physiological<br/>range of respiratory rate (8-40 breaths/min) and<br/>volume (<math>\frac{1}{2}</math>-4 liters). The output of the imped-<br/>ance respirometer correlated well with the output<br/>of the wedge spirometer in the quiet, seated<br/>subject. The problems of electrode configuration,<br/>body type, and electrode artifact are discussed.<br/>This system is a reliable and unencumbering<br/>method of monitoring respiratory rate and, poten-<br/>tially, respiratory volume. However, its use is<br/>severely limited by baseline shifts and motion<br/>artifact due to changes in electrode impedance.</p> | <p>UNCLASSIFIED</p> |
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