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# METHODS & DESIGNS

# Respiratory measurement: Overview and new instrumentation

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**Construction and application of a new device for obtaining accurate human respiration frequency measures and approximate respiration amplitude measures are described. The instrumentation required is small and unobtrusive and poses no hazard to the subject. Other devices commonly used for obtaining similar respiratory metrics are briefly reviewed and contrasted as to their limitations. Previous research efforts involving application of the new respiration instrumentation to dynamic environments are also discussed.**

This article describes instrumentation capable of providing waveforms representative of human respiratory behavior, from which breathing frequency is resolvable. Approximate measures of inspiratory amplitude may also be obtained by using the device, but its intended application is for breathing rate measurement. The major advantages of this new device are that it requires no electrical connection to a subject, does not inhibit subject movement, and is quite small, thus enabling unobtrusive, noninvasive data collection. Furthermore, the instrumentation is relatively straightforward and inexpensive. Wherever possible, only familiar electronic and hardware components have been specified to facilitate fabrication of the device. And typical data-recording hardware, such as stripchart and FM recorders, can be used. The fundamental part of the instrumentation is a "proximity" transducer that is attached to a subject's belt (or pant or skirt waistband) just in front of the abdomen. Filtering, conditioning, and recording circuitry are located remotely. Descriptions and circuit diagrams addressing all aspects of the instrumentation are provided herein.

## BACKGROUND

Metrics that directly reflect respiratory activity have been incorporated in a variety of psychophysical applications. Several pertinent studies are mentioned briefly here.

Perhaps the most prominent application of late is the investigation of breathing amplitude and, especially, frequency measures as correlates of incident operator mental workload in a variety of tasks. Respiratory rate measures have been applied as workload indicants in tracking tasks (Jex & Allen, 1970; Spyker, Stackhouse, Khalafalla, & McLane, Note 1), choice reaction time tasks (Ettema & Zielhuis, 1971; Mulder & Mulder-Hajonides van der Meulen, 1973), instrument-monitoring tasks (Gaume & White, Note 2), driving tasks (Casali, 1981; Lisper, Laurell, & Stenig, 1973), and aircraft-piloting tasks (Casali & Wierwille, 1982; Rahimi & Wierwille, 1982; Sun, Keane, & Stackhouse, 1976; Wierwille & Connor, 1983; Smit & Wewerinke, Note 3). However, in many of these and other psychophysical studies, respiration parameters are not the sole responses of interest. Other psychophysiological response measures are usually employed in a multivariate framework.

In many experimental situations, it is necessary to account for respiratory measurement artifacts in other measured physiological variables. Often, sudden changes in breathing rate and volume result in autonomic nervous system responses that may mask true effects resulting from changes in the manipulated variable (Stern, Ray, & Davis, 1980). For instance, the interaction of respiration and heart rate is well known (e.g., Ettema & Zielhuis, 1971; Scher, 1965). Also, Stern and Anschel (1968) documented the effects of breathing amplitude on heart rate, finger pulse volume, and skin resistance.

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## EXISTING PROCEDURES FOR OBTAINING RESPIRATORY PARAMETERS

Several techniques have been used to record breathing rate and amplitude in a variety of research situations. Each device has its own inherent advantages as well as problems; these are discussed in detail in Stern et al. (1980).

### Air Temperature Method

Thermocouples or thermistors are placed inside the nostril or at the open ends of the nostrils. The transducers are often clipped on the nasal septum of the subject. The output of the sensors (resistance for the thermistor and voltage for the thermocouple) changes with air temperature. Inspired air is cooler than exhaled air. Measurement of this temperature difference provides a means of ascertaining respiratory frequency. Although the transducers for this method are small, it is impossible to obtain respiration measures surreptitiously because the transducers are located at or in the nose, where it is intuitively obvious (to the subject) that breathing is being investigated. A "conscious" breathing pattern may result if the subject does not forget the presence of the thermosensor. Another problem is that certain subjects may ventilate primarily through the mouth rather than through the nose, rendering the thermosensor method useless.

### Electrode Method

Electrodes are placed on each side of the subject's chest, in the axillary areas. A low-amperage, high-frequency signal is applied, and impedance through the thorax is measured between the electrode sites. As the size (volume) of the thorax changes during inspiration and expiration, the impedance through the thorax varies. The measurement of impedance variations of as small as 1 ohm provides a metric of respiration frequency and a crude, relative measure of respiration amplitude (Stern et al., 1980). In addition to the typical placement, attachment, and artifactual problems accompanying the use of surface electrodes, the impedance method is quite obtrusive and requires relatively sophisticated equipment and supervision. Also, the application of this method in certain situations, such as in driving research, is limited by the fact that torso movements may cause impedance variations unrelated to respiration activity.

### Strain Gauge Method

A strain gauge is integrated with a length of rubber tubing or elastic strap placed snugly around a subject's chest or upper abdomen. Current of a low amperage is applied to mercury or another conductor contained in the tubing or strap. As the subject inhales, resistance in the circuit increases because the cross-sectional area of the conductor decreases as the thorax expands. Typically, the output of the strain gauge is wired to a Wheatstone bridge to produce a dc output signal that is directly proportional to resistance variations accompanying each inspiration and expiration. As noted by Stern et al. (1980), the amount of amplification and conditioning circuitry required is minimal due to the substantial amplitude of a typical signal. Strain gauges are quite popular as respiration transducers, but they present several notable problems. First, there is considerable variation in optimal placement of the tubing or strap among subjects. Over-the-clothing placement on a female is difficult to attain, unless the subject is wearing tight-fitting garments. Additional problems include obtrusiveness of the strain gauge transducer and susceptibility of the conductor to continuity breaks, such as those due to air bubbles in the mercury.

### Air-Pressure Pneumograph

In the pneumograph method, an air-filled length of flexible tubing is stretched around a subject's chest. This tubing is connected to a pressure sensor, amplification circuitry, and a recording system. During inspiration, the chest expands and causes the tube to stretch, which increases the pressure inside the tube. During exhalation, a decrease in pressure is realized inside the tube. This technique yields an accurate measure of breathing rate but only relative indications of amplitude. The obtrusiveness of the pneumograph technique is comparable to that of the strain gauge method. Furthermore, location points on the chest are highly variable across subjects, the tubing may slip or roll on the body, and the elastic tubing may cause discomfort, especially in long experiments.

### Other Techniques

Several additional methods for obtaining certain pulmonary measures and gas component analyses exist. Spirometry is particularly useful in applications in which volumetric indexes such as vital capacity and its subdivisions are required (Astrand & Rodahl, 1977). In this method, a subject breathes into the spirometer via a wide-bore tube. Volume displacement in the spirometer corresponds to volume change in the lungs, and a measurement in liters is obtained. Closed-circuit breathing methods (e.g., gas dilution), utilizing a closed spirometer in conjunction with a gas component analyzer, are employed for determining such pulmonary metrics as functional residual capacity and end-tidal $CO_2$ levels. A measure of respiration rate may also be extracted from stripchart recordings of the $CO_2$ waveform. A recent application of this technique to an investigation of the effects of psychological stress on respiratory behavior is discussed in Suess, Alexander, Smith, Sweeney, & Marion (1980). Although spirometric and related methods are essential for obtaining certain respiratory indexes, such as functional residual capacity, the apparatus required is quite cumbersome for measuring respiration rate. In particular, the wide-bore breathing tube or oxygen face mask used for connecting the subject to a spirometer or gas analyzer is restrictive and obtrusive, which precludes the use of such methods in certain applications.

## NEW INSTRUMENTATION FOR RESPIRATORY FREQUENCY

The need for a new type of respiration frequency measurement apparatus arose prior to the undertaking of a driving experiment in the Vehicle Simulation Laboratory at Virginia Polytechnic Institute and State University.[1] Respiration rate was a candidate for investigation as one of four possible physiological correlates of the onset of simulator discomfort (mild vertigo, disorientation, etc.) in a moving-base driving simulator (Casali, 1981). (That particular simulator had no prior history of eliciting simulator sickness; however, its subsystems were modified to simulate certain aspects of other simulators known to induce discomfort in subjects.) The usual respiration measurement techniques discussed above were rejected for use in this experiment for various reasons. First, the presence of curvature and crosswind gusts in the lengthy driving task elicited upper body and shoulder movement that may have resulted in separation of electrodes from the skin or slippage of strain gauge or pneumograph tubing. The length of the experiment also prohibited the wearing of tubing that pressed against the skin for extended periods. Furthermore, it was desirable to ascertain respiration rate in a surreptitious manner. This would have been quite difficult with electrodes or thermosensors. The function of the proximity transducer described herein appeared not to be obvious to the subjects in the driving experiment. Perhaps this was due to the location of the device (out of the line of sight near the beltline) and due to the fact that the small transducer did not come into physical contact with the subject. Furthermore, the transducer was easily attached in about 10 sec, therefore, the subject did not have to sit patiently while electrodes or thermosensors were attached, and thus was not given an opportunity to become curious about their function. At the end of the session, each of the subjects was told the function of the transducer. Finally, because of the split sex sample, "under-the-shirt" strain gauges, pneumograph tubing, and electrodes were not desirable. The proximity transducer is worn externally to a shirt or blouse, and the presence of the cloth in no way inhibits the accuracy of the waveform.

## INSTRUMENTATION DESIGN

The proximity transducer is the only part of the apparatus mounted directly on the subject. Circuitry for the transducer is housed in a 45-mm-long, 5-mm-diam rigid plastic tube (see Figure 1). The input signal for the transducer circuitry is provided by a 15 x 20 mm antenna plate made of 30-ga aluminum stock. The plastic tube is friction-fitted in a nylon cable clamp for adjustment purposes. The cable clamp is bolted (with a size 4-40 wing nut) to a twisted piece (90-deg twist) of flat 20-ga aluminum stock, 10 mm wide by 40 mm long. This aluminum support is then bolted or welded to another piece of malleable aluminum stock, 7 mm wide by 65 cm long, which is bent into the shape of a belt, as shown in Figure 1. This belt is split at the rear (at the location of the subject's spinal column) so that it can be spread apart and slipped around the subject's waist. Normally, the flexible metal belt is simply positioned slightly above the subject's belt or skirt waistband (see Figure 2).

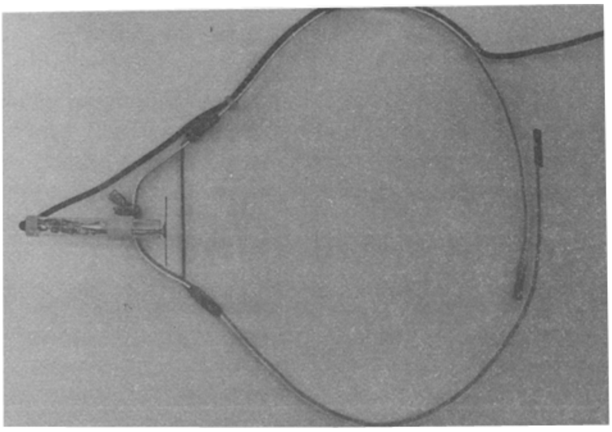

**Figure 1. Respiration transducer and mounting belt.**

The sole function of the belt is to locate the proximity transducer on the subject and to provide routing for the three-conductor transducer output cable. This cable exits the plastic tube at the opposite end from the antenna plate and is routed along the outside of the belt behind the subject (see Figure 1). Small nylon wire ties are used to secure the cable to the belt. The belt itself should not have enough "spring" to press so tightly against the subject that it causes discomfort. A malleable metal should be used, because the belt then may be

**Figure 2. Respiration transducer mounted on subject's abdomen.**

bent slightly to reduce tension for large subjects or to increase tension for thin subjects. If the belt tends to slip up or down on the abdominal area, miniature metal clothespin-type clamps may be used to clip the belt to the subject's clothing. In our experience, however, slippage of the belt has not been a problem.

From data on approximately 140 subjects in four experiments, it was found that the optimal placement of the antenna plate for obtaining respiration rate is directly in front of the upper abdominal area, 80 to 100 mm below the xiphoid process of the sternum. This positioning is obtained using mounting belt and wing-nut adjustment. With the abdomen fully relaxed, the antenna plate should be located approximately 20 mm away from the body. This adjustment is made by sliding the plastic tube within the cable clamp. Shirt or blouse material does not interfere with transducer functioning; however, if the subject is wearing a heavy metal belt buckle, it should be moved to one side or removed completely.

The proximity transducer relies on contraction and protrusion of the abdomen during breathing (the contraction and protrusion are produced by elevation and depression of the ribs and upward/inward and downward/outward diaphragm motion). The transducer senses this motion and provides a voltage signal output indicative of abdominal horizontal position. A circuit diagram and component specification for the transducer are shown in Figure 3. Basically, the transducer and the subject's abdominal region represent a capacitive coupling. The subject's body acts as an antenna for typical ambient electromagnetic noise present in the laboratory. The antenna plate receives this noise, the amount of which is determined by the instantaneous abdomen-to-plate distance. As this distance decreases, such as when the abdomen protrudes during inhalation, the strength of the capacitive coupling increases. As the distance increases, the coupling decreases in strength. The noise signal provided by the transducer is subsequently applied to a gain and isolation circuit (Figure 4), and finally an amplifier-signal conditioner circuit (Figure 5) is used to provide a filtered, slowly varying voltage signal output.

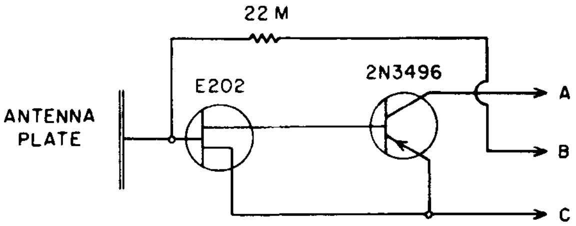

Figure 3. Respiration transducer circuitry.

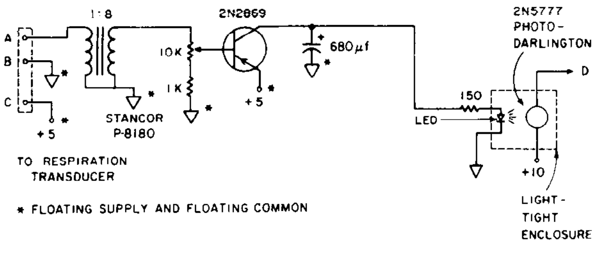

Figure 4. Respiration gain isolation circuitry.

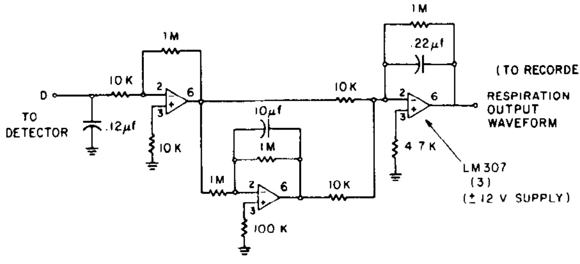

Figure 5. Respiration amplifier-signal conditioner circuitry.

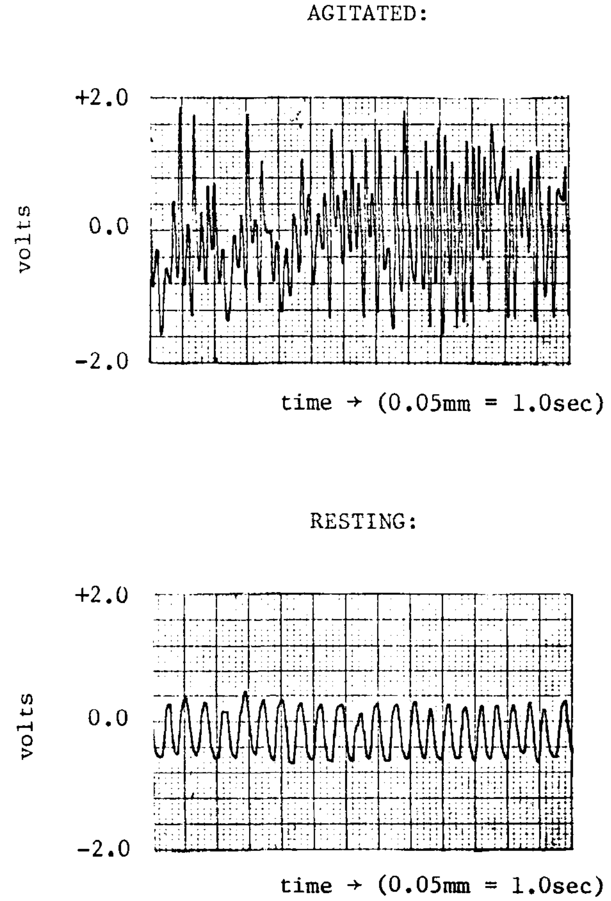

Figure 6. Typical recording of respiratory activity, agitated and resting.

The conditioned transducer output signal is displayed on a stripchart recorder, such as a Grass Model 7DWU16P. In the event that the recorder pen slews off scale due to sudden deep breaths, the amplifier-conditioner circuit forces the pen to return to a normal center position prior to subsequent breaths. Of course, for each subject, recorder gain and zero center settings need to be carefully established prior to a data run. During quiet breathing, it is recommended that recorder amplifier gain be adjusted such that attained average zero-to-peak amplitude is 60% of full scale. Recommended chart-drive speed for resolving breathing frequency is 1.0 mm/sec. Respiratory frequency may then be easily obtained through a visual count of waveform peaks on either side of the stripchart center line. Each pair of peaks (one on the left and one on the right) corresponds to a single breath consisting of one inhalation and one exhalation. Approximate measures of depth of inspiration may be obtained from the zero-to-peak amplitude of each inspiration-produced waveform peak. A typical recording of both resting and agitated respiration activity obtained by using the device is shown in Figure 6.

It should be stressed that this instrumentation is designed such that the subject must be "floating" (ungrounded in the circuitry) for proper operation. Also, for maximum sensitivity, the circuit should be "capacitively coupled" to the ac line. This is easily accomplished by using a plug-in-type power supply. Since power is supplied from a power line, a low-current transformer must be used for isolation. Even though there is no electrical connection between the subject and the apparatus, the experimenter must ensure that the apparatus does not present an electrical hazard (as with any equipment connected to a power line).

## RECENT APPLICATIONS

Since the initial application of the respiration transducer to a driving simulation study, it has been employed in three aircraft studies (Casali & Wierwille, 1982; Rahimi & Wierwille, 1982; Wierwille & Connor, 1983). In these experiments, pilots' respiration rates in number of breaths per minute were obtained during flight in a moving-base aircraft simulation. Within-subject respiration rate trial-to-trial stability was quite high in all three studies. After use with more than 140 laboratory subjects of varying sizes and breathing habits, no significant problems have surfaced with the respiratory instrumentation.

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## NOTE

1. R. E. Cordes conceived this new method of obtaining respiration rate and developed the prototype equipment. Questions regarding the circuitry should be directed to R. E. Cordes, IBM General Products Division, Department 76V, Building 312, Tucson, Arizona 85744. W. W. Wierwille refined the signal-conditioning circuit for use in laboratory research at Virginia Tech.

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