Impedance Spirometry in Clinical Monitoring*

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There are certain places, such as the operating-theatre and the intensive therapy unit, where it is impossible to keep a finger always on a patient's pulse or a constant watch on his breathing. In these circumstances it is customary to employ various types of monitor. Ideally, by using such a machine, one should be able to tell at a glance that the patient is breathing and his heart is beating, even if he cannot be directly observed. Most of the apparatus in common use falls short of this ideal. We have therefore been examining changes in the electrical impedance across the chest as a method of monitoring patients.

Methods of Respiratory Monitoring

Many methods of respiratory monitoring have been employed. The anaesthetic reservoir bag gives a useful qualitative indication of spontaneous respiration, but it cannot be calibrated and it is in any case seldom used in the artificially ventilated patient. Thermistors and pressure transducers placed in the airway also give an indirect indication of respiration. Some mechanical ventilators have calibration marks which purport to measure the tidal volume; these tend to be inaccurate, difficult to read, and in any case capable only of measuring the volume leaving the machine. Only the spirometer and the pneumotachograph can measure accurately the volume of respiration. All these methods share the disadvantage of being placed in the airway, where they will fail to detect disconnection of a ventilator, if this is of the type which continues to function in the presence of a leak. The external strain-gauge pneumograph lacks this drawback but it tends to slip and has not proved popular. Pressure transducers placed in the oesophagus give an even less direct indication of respiration.

For the heart beat the E.C.G. is the best way of detecting arrhythmias and disturbances of conduction, but it is capable of giving a fairly normal-looking trace in the absence of any significant forward flow of blood. Peripheral pulse monitors, apart from their tendency to produce artifacts, err in the other direction by indicating no-flow under conditions of skin vasoconstriction when the cardiac output may be little disturbed.

In any event it is undesirable to have a multiplicity of monitors attached to a patient. They can be such a nuisance to the medical and nursing staff that they may not be used in situations where they might otherwise be helpful. The time needed to apply and adjust them may be too long to be acceptable, particularly in the theatre or recovery room. A variety of leads and transducers attached to the chest and arms may cause dangerous confusion to the attendants and alarm to the patient.

A less obvious disadvantage of many currently available monitors lies in the way in which the information is displayed. Dial displays are difficult to understand if they show rapidly changing variables such as respiration or the arterial pulse, and for this reason the information they impart can only be

of a qualitative nature. In such a case a blinking light will often be more appropriate. Pen recorders are essential for the proper interpretation of the E.C.G., the pneumotachograph, and spiograms, but it is inconvenient and expensive to use them for continuous display purposes at any useful paper speed. For this reason an oscilloscope is best for continuous monitoring purposes. Most oscilloscopes used for this purpose have screens of 3-5 in. (7.5-12.5 cm.) diameter and are far too small to be seen at any distance.

We believe that for any method of monitoring the form of display must be appropriate to the information displayed. Rapidly changing variables should be appreciated as they occur, and for this reason an oscilloscope or a chart recorder is needed to show individual waves. For less rapidly changing variables, such as respiration rate, heart rate, or mean arterial pressure, a meter or digital display is more appropriate. For slowly changing variables such as body temperature a meter can also be used. In addition to this the display should be easily visible from a distance—for example, from across the patient's bed—particularly in the case of the most rapidly changing variables. Lastly, we feel it is important that the criteria which are monitored should be easy to comprehend. This is important when the monitor is to be watched by nurses who may not, for example, understand the significance of changes in rather indirect measurement such as the digital pulse wave.

Impedance Spirometer

Atzler (1935) attempted to measure cardiac activity by following changes in electrical impedance across the chest. He noted at the same time that the transthoracic impedance varied with respiration. Other workers later attempted to record respiration by this means, but modern interest in the method is due largely to the work of Geddes *et al.* (1962b). They passed a small high-frequency current through the chest and were able to demonstrate the relation between changes in the volume of air breathed and changes in electrical impedance. Later work (Kubicek *et al.*, 1964; Pallet and Scopes, 1965; Baker *et al.*, 1965) confirmed that, though the calibration varied, this relation was more or less linear. The slope of the line varied between individuals and depended, moreover, on the position of the skin electrodes, the frequency of the current applied, and the posture of the subject.

Most writers have noted small variations in the tracing synchronous with the heart beat. While this has generally been treated as an artifact we regard it as indicative of pulsatile changes in the volume of blood in the thorax. It is not necessary to assume that this variation is due to change in the size of the heart during each beat. Kubicek *et al.* (1966) concluded that it was probably due to the pulsating pulmonary blood flow. In some of our subjects, however, complex wave-forms have been observed which might be due to changes in heart size (see Fig. 2).

Geddes *et al.* (1962a) showed that it was possible, by the employment of suitable filtering circuits, to record the electrocardiogram from the electrodes used to measure transthoracic impedance. We therefore employ this technique in order to display the E.C.G. at the same time as impedance changes.

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The apparatus we are using consists of a 100 kc./s. oscillator that supplies a constant current of 200 μ A to two electrodes attached to the chest wall. The signals across these electrodes are separated into E.C.G. and 100 kc./s. components. The E.C.G. is fed to a conventional display system and the 100 kc./s. is amplified and rectified to d.c. and then subtracted from a reference potential to give the respiration signal required. We have found it preferable to employ three skin electrodes for long-term monitoring because the addition of an indifferent electrode considerably reduces artifacts on impedance and E.C.G. displays caused by contact with the patient. The electrodes are stainless-steel discs of 2.3 cm. diameter coated with Cambridge electrode jelly. They are attached to the skin by adhesive paper tape.

The outputs of the impedance spirometer and E.C.G. amplifier are displayed on a large screen oscilloscope (Lan Electronics L S 19). The tracings may also be recorded on magnetic tape or on a paper chart recorder. The impedance trace appears as a line of small waves, due to the heart beat, with larger waves due to respiration superimposed (see Figs. 2-6).

Clinical Use

For monitoring purposes the measuring electrodes are attached to the patient's chest at the level of the sixth rib in the mid-axillary line (Fig. 1). At this level the maximum impedance change is seen during respiration (Geddes *et al.*, 1962). The indifferent electrode is placed on the manubrium sterni. Use of a standard arrangement makes it easy for nurses to remember the position. It also allows the conscious patient a good deal of freedom of movement, and, perhaps more important, he is not aware of the presence of the electrodes once they have been applied. The electrodes can be applied quickly without too much disturbance of the patient. We have found that they can be left on for up to a week without causing irritation to the skin. However, we have experienced difficulty in keeping them attached to the skin in very obese subjects and are at present considering alternatives.

After a few minutes the tracing settles down to the pattern shown in Figs. 2-6. Baseline stability is good so long as the patient remains still. Movement and postural changes, such as lying on one side, alter the basal impedance, but the baseline can be restored by altering the high-frequency gain (Pallett and Scopes, 1965) or by means of an automatic baseline-restoring circuit. In practice this represents little disadvantage because the patients we monitor are usually immobile for one reason or another. We have occasionally encountered tracings which appeared inverted, and this has been found to result from wrong positioning of the electrodes or from poor skin contact. It is noticeable that in children the cardiac component of the tracing is much more prominent than in adults.

Our intensive therapy unit nurses have little difficulty in understanding the significance of the tracings. They recognize the E.C.G. immediately, and, after seeing the position of the electrodes, soon decide that the other tracing shows respiration. The cardiac component of the impedance tracing is less often recognized immediately, but is understood once it

has been explained. As the height of the respiratory waves is proportional to the tidal volume the system is meaningful, unlike a tracing of airway or oesophageal pressure. This enables the observer to form the same appreciation of the patient's respiration as can be obtained by close observation of the movement of the chest.

Calibration is carried out by measuring the height of the tracing at the same time as the breath is measured with a spirometer. For monitoring purposes we use either a Wright spirometer or a calibrated concertina bellows which can be used to give a breath of known volume to an apnoeic patient. These methods are accurate enough for clinical purposes, in spite of the relatively large standard deviations of the impedance changes reported by Kubicek *et al.* (1964). For adults we normally employ a sensitivity of 1 cm./100 ml. volume change, but in children we usually increase this to 2 or 3 cm./100 ml.

We have found, as we had originally hoped, that changes in tidal volume and upper airway resistance are immediately apparent. We regard the display of these changes as an essential property of any respiratory monitoring system. Fig. 2 shows the effect of clamping the endotracheal tube connexion in a spontaneously breathing anaesthetized patient. Fig. 3 shows the same procedure in a fully relaxed anaesthetized patient receiving artificial ventilation. In both these cases the small cardiac waves are seen to persist while the

FIG. 1.—Position of electrodes on patient's chest. The measuring electrodes are in the mid-axillary line and the indifferent electrode on the manubrium sterni.

FIG. 2.—Tracing taken from a spontaneously breathing anaesthetized patient. The larger variations are due to respiration and the smaller to the heart beat. The black line shows when the endotracheal connexion was clamped, causing a complete obstruction to respiration. The respiratory wave disappeared in spite of the patient's efforts to breathe, but the cardiac wave remained. (Paper speed 5 mm./sec.) FIG. 3.—Tracing taken from the same anaesthetized patient during artificial ventilation after receiving a relaxant. Only the cardiac waves could be seen when the airway was clamped for 12 seconds (black line). (Paper speed 5 mm./sec.) FIG. 4.—Recording from the same patient when the airway was partially clamped (black line) during artificial ventilation. The tidal volume fell to about half its previous value. (Paper speed 5 mm./sec.) FIG. 5.—Tracing showing the effect, again in the same artificially ventilated patient, of disconnecting the ventilator (black line). As in Fig. 3, only the cardiac waves can be seen. (Paper speed 5 mm./sec.)

respiratory waves are absent. In Fig. 4, recorded from the same relaxed patient, the airway is only partially obstructed, resulting in an obvious reduction of tidal volume. Fig. 5 shows the effect, again in the same apnoeic patient, of disconnecting the ventilator. This pattern is indistinguishable from that shown in Fig. 4, demonstrating that this technique reveals the essential point—namely, that ventilation of the lungs has ceased. So far as we know this is the only method of monitoring which cannot give a wrong indication in these circumstances.

It is also possible to study the shape of the respiratory wave-form with the impedance spirometer. The tracing follows closely all changes in the volume of air in the lungs, so that it is possible to measure not only the tidal volume but the rate of change of volume, both in inspiration and in expiration. Fig. 6 was recorded on a patient ventilated with a Barnet Mark III ventilator. This machine, though theoretically a constant pressure generator, in practice operates as a

FIG. 6.—Tracing showing the respiratory wave-form when using a Barnet Mark III ventilator. This machine functions as a constant flow generator and the upstroke of the respiratory wave shows the expected straight line. The downstroke, as the patient expires to atmosphere, is exponential. (Paper speed 5 mm./sec.) FIG. 7.—Tracing showing the wave-form when using an East-Radcliffe ventilator to produce the same tidal volume as in Fig. 6. In this case both the upstroke and the downstroke are exponential. This wave-form is typical of a constant pressure generator. (Paper speed 5 mm./sec.)

constant flow generator (Mapleson, personal communication) and the tracing shows the expected straight line during the inspiratory phase. Fig. 7 was recorded when the same patient was being ventilated with an East-Radcliffe ventilator at approximately the same rate and tidal volume. In this case the tracing shows the exponential curve expected of a constant pressure generator. In both these tracings the expiratory portion is identical, being an exponential decay as the patient expires to atmosphere. The technique may therefore prove helpful in the treatment of asthmatics in whom this decay is prolonged because of the increased lower airways resistance.

Summary

A technique for monitoring respiration is described which is simple to use and simple to understand. Three electrodes are attached to the patient's chest and changes in trans-thoracic electrical impedance are displayed on an oscilloscope. This tracing reflects the volume of air in the lungs so that the tidal volume, respiratory rate, and respiratory wave-form can be immediately appreciated by those attending the patient.

Additional advantages are that an E.C.G. can be obtained from the same electrodes and that the impedance tracing shows small variations in time with the heart beat. It therefore gives a valuable indication of the function of the heart as well as of respiration. The display provides direct, reasonably accurate, and conceptually simple indications of these two vital factors, important points where nurses are concerned. We feel that this technique is worthy of further trial.

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Haemoglobin E and α -Thalassaemia*

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Haemoglobin Bart's was first described by Ager and Lehmann (1958). The fast-moving haemoglobin earlier reported by Fessas and Papaspyrou (1957) is believed to be identical with Bart's (Fessas, 1959). This haemoglobin has been found by Hunt and Lehmann (1959) to consist entirely of γ -polypeptide chain, thus having the molecular formula of γ_4 ; Hbs A, F, and A_2 are $\alpha_2\beta_2$, $\alpha_2\gamma_2$, and $\alpha_2\delta_2$ respectively.

Hb Bart's, in extremely variable amount, has been found in conditions ranging from the asymptomatic newborns (Tuchinda *et al.*, 1959; Lie-Injo, 1959; Vella, 1959; Hendrickse *et al.*, 1960; Fessas, 1960; Lie-Injo and Ti, 1961; Schneider and Haggard, 1961; Minnich *et al.*, 1962; Silvestroni and Bianco, 1962; Weatherall, 1963) to the lethal Hb Bart's hydrops foetalis

syndrome (Lie-Injo *et al.*, 1962; Banwell and Strickland, 1965; Diamond *et al.*, 1965; Wong, 1965; Pootrakul *et al.*, 1967). Apart from its presence in minute amount in the cord blood of apparently every newborn, the occurrence of Hb Bart's is believed to be a result of α -thalassaemia gene. The latter depresses α -chain synthesis, resulting in excessive γ -chains, which then polymerize to the tetrameric form- γ_4 .

In Thailand Hb E, β -, and α -thalassaemias are prevalent (Na-Nakorn *et al.*, 1956; Flatz *et al.*, 1965; Wasi *et al.*, 1967). These genes, in different combinations, give rise to various conditions and diseases, such as β -thalassaemia homozygosity (Hbs A+F), β -thalassaemia-Hb E disease (Hbs E+F), and Hb H disease (Hbs A+H). Beginning from 1961, we have frequently encountered another disease characterized by the presence of three haemoglobins, A, E, and Bart's. Genetical data indicate that individuals with this disease inherit three abnormal genes—namely, a classical or α -thalassaemia, a milder

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