Recording respiratory function by x rays: basic principles

RAOUL KOURILSKY, MAURICE MARCHAL, AND
MARIE-THÉRÈSE MARCHAL

From the Hôpital Saint-Antoine, Paris 12^e

Accurate methods for recording respiratory function have been developed in the last 30 years. They were derived from the conventional techniques used in physiology and biochemistry. We thought that x rays might provide a new means of assessing respiratory function and so prove useful in the investigation of the physiology of respiration.

Although auscultation is a sound-recording of the changes induced in the distension of the alveoli after the movements of air through the bronchioli, 'dynamic fluoroscopy' is an optical record of the variations of translucency in inspiration and expiration, depending on the changes in the density of the lung.

During forced inspiration the density is low, and only a small quantity of x-radiation is absorbed by the lung. Conversely, during expiration the density of the lung increases, the passage of the x rays is impeded, and the image darkens. Brille and Hatzfeld (1955) showed that the results obtained with 'dynamic fluoroscopy' are much more accurate than most observers would expect: emphysema, trapping, and sometimes pulmonary infiltrations can be located in the upright and supine positions. Unfortunately, too much radiation may be given to the observer and the patient, but their paper suggested the value of densitometry as a method of recording ventilation.

It was necessary to find a substitute for the human eye, and we thought that, instead of recording the optical variations of the fluoroscopic screen, the quantitative changes of the flux of x rays after they had crossed the thorax could be measured (Fig. 1).

A first attempt was made by one of us (M. M.) in 1934 to register the invisible variations of density of the arterioles at the periphery of the lung during systole and diastole.

In 1946 a group was created in our clinic to reinvestigate the problem. We had to wait for sufficient progress to be made in the field of

electronics before it could be solved. Receptors such as ionization chambers were suitable for laboratory work but too delicate for medical practice. Geiger counters required a complicated connecting system and carefully calibrated filters in order to screen out the peripheral sources of ionization (cosmic rays and ambient radioactivity).

The correct solution was to use photo-electric cells, photomultipliers, or scintillators, through which the x rays were transformed into electronic pulsations. These in turn were fed into an electronic amplifier connected to an electromagnetic galvanometer.

Marchal (1946) recorded the pulsations of the peripheral arterioles of the lung by the densitometric method.¹ He applied the same principle to measure the local ventilation (Marchal, 1949).²

The method was modified by Marchal and Marchal (1954) to register the total ventilation³ and the simultaneous recording of each lung separately (Marchal and Marchal, 1957).

SIMULTANEOUS DENSITOMETRIC RECORDING OF THE VENTILATION OF EACH LUNG

(1) The x-ray source is a generator of a self-rectifying type (70 kV, 2 mA). The radiations are interrupted 50 times per second and filtered by 3 to 5 mm. of aluminium.

(2) The flux of x rays penetrates into the thorax, then falls on the screen (50 cm. x 43 cm.), inducing a fluorescence of the same 50 cycles per second.

(3) The radiations are received on the photocathode of an RCA 931 photomultiplier which is secured in a light-tight box fixed in front of the screen. They are transformed into electronic pulsations of the same frequency (50 periods) which are channelled into an electronic amplifier (Fig. 1).

¹Cinédensigraphie

²Statidensigraphie locale

³Statidensigraphie globale

FIG. 1. Diagram showing densitometry of ventilation by x rays. RL = right lung; LL = left lung; FS = fluoroscopic screen; B = light-tight box; PH1 and PH2 = photomultipliers; A1 and A2 = amplifiers; S = light source; PR = photoelectric record.

In such a system the amplitude of the electronic pulsations is proportional to the luminescence of the screen, which is itself proportional to the quantity of x rays leaving the thorax after irradiation.

Fifty electronic pulsations are recorded in one second. If the paper revolves at 2.5 cm. per second, the succession of waves cannot be seen and a homogeneous band appears on the graph; its breadth is the amplitude of the pulsations.

It is always necessary (since the filters fitted in the amplifier may alter the waves) to verify that 'square wave top signals' emerge without distortion.

The efficiency of the system is appreciated by the curve of densities obtained by irradiating layers of increasing depths, made of an absorbent isotropic substance (solid paraffin or plastic: perspex). The depths are plotted as abscissae, and

the breadths of the densigram as ordinates. The curve is exponential. But if a semi-logarithmic paper is used, a straight line is obtained (Fig. 2). It demonstrates the linearity of the densities recorded with the apparatus.

If the method is applied to the thorax, it must be remembered that the x rays penetrate successively through the thoracic wall and through the lungs, and that the density is not homogeneous. But in inspiration and expiration the absorption of the radiations by the thoracic wall and the other solid formations inside the thorax is the same. Therefore the variations of the *amplitude* of the pulsations are proportional to the variations of the density of the lung itself, and essentially to the variations of the quantities of air inside the lung. The variations in the quantity of blood during respiration are too small to be recorded by the photo-electric cell used in this method. Therefore they do not interfere with the recording of the ventilation.

A continuous record of the ventilation is obtained (Fig. 3).

The ventilation of each lung is recorded separately. Two photomultipliers and two amplifiers are necessary. The patient is not connected to any apparatus, has no mouth-piece, and breathes freely; the respiration is not modified by any physical contact with the recording instruments, or the record may be taken with the patient unaware.

With the powerful photomultipliers now available, *i.e.*, the Radiotechnique 152 AVP tube, the quantity of filtered x rays necessary for the recording is less than one-tenth of the dosage required for standard fluoroscopy. The radiations are invisible on the screen to the physician's eyes and can only be detected by the photomultiplier. The room may even be lit.

Great care must be taken to cut off any stray light which might infiltrate on the periphery, especially in the axillary regions. Opaque masks are fastened on the patient's back for this purpose.

A recording of the respiration of both lungs appears on the same graph (Fig. 3). The curves are superimposed. A slight displacement is necessary for the convenience of reading, and the right lung is recorded above the left. Both are synchronous.

The 'forced expiration test', known in France as Tiffeneau's test, is easily recorded. The electronic and spirographic curves are exactly the same. But since the two lungs are recorded simultaneously, the slightest discrepancy is visible.

FIG. 4. Local statidensigraphic record in an apparently healthy adult, aged 45 years. On the right side, the ventilation varies normally from apex to base; the ventilation of the left base is slightly impaired.

DENSITOMETRIC RECORDING OF LOCAL VENTILATION

Local changes of ventilation may be registered by the densitometric method on small areas of the lung (20 mm. $\times$ 5 mm.) (Fig. 3). Shielded photo-electric cells provided with a small fluorescent screen and a horizontal slit of the same dimensions (20 mm. $\times$ 5 mm.) are used for this purpose.

The cell is fixed on five different areas of the anterior thoracic wall for each lung: (1) subclavicular, (2) upper middle, (3) middle, (4) inferior

middle, and (5) base: it is necessary to keep away from the mediastinum. Careful attention must be paid to the position of the cell in order to avoid interference by the ribs: the control is made on the conventional screen.

A small dosage of strongly filtered x rays (of the same 70 kilovoltage) is required.

It is clearly seen from the tracings (Fig. 4) that the intensity of the ventilation, as is already known, varies in different areas in normal individuals. The slightest alteration of the ventilation is visible everywhere.

DENSITOMETRIC RECORDING OF PULSATILITY OF PERIPHERAL ARTERIOLES OF THE LUNG

At first sight the pulsatility of the vessels does not appear relevant to respiratory function. However, since the walls of the pulmonary arterioles, compared with those of the systemic circulation, are thin and react to the influx of blood more like veins, the pulsatility is proportional to the volume and to the velocity of the blood stream.

These variables also depend on the intensity of ventilation. The correlations have been studied in another paper, but the basic principles of recording the pulsations will be described here.

The opacity of the vessels increases during systole, when they are filled with blood, and decreases during diastole. These variations (invisible to the human eye) are measured by a 152 AVP Radiotechnique photomultiplier fixed between the thorax and the fluoroscopic screen. The front of the photomultiplier is fitted with a small fluoroscopic screen (20 mm. $\times$ 5 mm.) (Fig. 5). The x rays, after penetrating the vessels, leave the thorax and fall on the screen of the multiplier. They are transformed into fluorescent optic waves and then changed into electronic pulsations. After amplification they are channelled into an electronic galvanometer.

The densitometry of the vessels is clearly more difficult to record than the densitometry of the ventilation.

1. A four-valve rectifier generator of 100 cycles must be used.

2. The photomultiplier must be fixed at the periphery of the lung, away from the pulsations of the major vessels. The pulsations of the

FIG. 5. Diagram of the local densitometry of ventilation and of the pulsations of the lung as shown by x rays. 1, X ray tube (70 kV., 100 mA); 2, thorax; 3, x rays leaving the thorax; 4, small fluoroscopic screen (25 mm. $\times$ 5 mm.); 5, light beam; 6, photocathode of the photomultiplier; 7, dynodes; 8, electronic wave leaving the photomultiplier; 9, lead-armoured light-tight box; 10, slit (25 mm. $\times$ 5 mm.); 11, photomultiplier tube.

bronchial arteries and the pulmonary arteries do not interfere. They cannot be recorded.

3. The sequence of the pulsations must be simultaneously checked on the same graph against the electrocardiogram. The pulsation of the arterial pulmonary vessels starts from 5 to 1/100 of a second after the R wave, expands abruptly, and declines progressively with several dicrotic waves. Transferred pulsations of aortic, auricular, or ventricular origin differ in sequence and appearance.

4. The basic difference in density between stocky

FIG. 6. Pulsatility of the peripheral arterioles of the right lung in different areas in a normal individual. A, subclavicular; B, superior middle; C, middle; D, base. The large bands on the left are the records made on a fraction of the 'ripple'—the alternating current issuing from the photomultiplier tube—necessary for the calibration (see text). RL = right lung; LL = left lung.

and lean individuals must be corrected, and the quantity of x rays shed by the source must be adjusted accordingly. Marchal and Marchal (1951) and Marchal, Marchal, and Kourilsky (1960) developed a special method of calibration for that purpose. The correction is operated on a fraction of the alternating current issued from the photomultiplier tube, carrying the modulations induced by the pulsations of the vessels. The breadth of the band is proportional to the quantity of x rays that actually penetrates the photo-electric cell (Fig. 6).

5. The photomultiplier must be carefully calibrated.

6. The lung is shielded with lead by a diaphragm fixed on the back, except for the area where the pulsations are being recorded.

7. The records are taken in apnoea during moderate inspiration. The patient is secured to avoid any movement.

8. Kilovoltage (intensity of the x rays) and tension (volts) applied to the photomultiplier must remain constant. The amplification must be identical for both lungs.

The tracings disclose important differences between normal individuals and, in the same individual, between different areas.

Mensch (1957) showed that it is possible to calculate an 'index of pulsatility'. The index is the ratio of the mean amplitude of the pulsations to the quantity of x rays received by the photo-electric cells. This coefficient is calculated separately for each area. The sum of these coefficients is the index for the entire lung (coefficient P).

We have shown in another paper that this coefficient P can be correlated with the ventilation so as to give a close appreciation of O_2 consumption (Marchal, Mensch, and Marchal, 1957).

A COMPARISON WITH OTHER METHODS

Several electronic methods based on densitometry were applied later to the transcription of pulsatility and ventilation, using a different terminology.

Electrokymography has been described by Chamberlain (1947), Luisada and Fleischner (1948; 1949), Morgan, Gould, and Vanallen (1948), Boone, Ellinger, and Gillick (1949) and Engström, Kjellberg, Persson, and Rudhe (1949).

However, their techniques are not identical with ours: most are lacking any system of automatic calibration for the variation of the quantity of x rays penetrating into the photo-electric cell.

Several methods for the recording of ventilation have been described by Andrews, Jensik, and Pfisterer (1959) and Steiner, Laws, Gilbert, and McDonnell (1960), and these have confirmed our previous results.

SIMULTANEOUS RECORDING OF PULSATILITY AND VENTILATION IN THE SAME AREA OF THE LUNG

Marchal, Marchal, and Benardeau (1964) obtained simultaneous recordings of pulsatility and ventilation in a local area of the lung. The channels are adjusted to a *single* photomultiplier, and a *single* fluorescent screen is fixed in front of the photomultiplier. The ventilation and the pulsations appear on the same photographic film. If the patient is asked to breathe during the recording, the simultaneous variation of both parameters is observed. The use of a single photo-electric cell, instead of two, curtails the length of the procedure by 50% and increases the accuracy.

This technique opens a new field of investigation. It becomes possible to study the influence of inspiration and expiration on the pulsatility of a restricted area of the lung, and to develop an electronic calculation of the index of pulsatility.

The ratio of the mean amplitude of the pulsations to the quantity of x rays received by the amplifier is calculated by dividing the former by the mean amplitude of the densographic band. Since the recordings are simultaneous, a special electronic device known as the 'quotientometric system' is applicable. It calculates automatically the ratio of the arithmetic mean (A) of the modulation of density induced by the pulsatility to the mean value (E) of the non-modulated density. This information is automatically transcribed together with the ventilation, the pulsatility, and the electrocardiogram onto the same graph.

SUMMARY

New techniques for the exploration of respiratory function, using x rays, are described. They are based on the measurement of the flux of x rays leaving the lungs after irradiation and their transformation into optical waves by a fluoroscopic screen or a scintillator, and electronic pulsations through a photomultiplier. They are amplified and recorded by an electromagnetic galvanometer.

Continuous photographic records of the spontaneous respiration of each lung are obtained simultaneously. Local ventilation is recorded likewise on selected areas of each lung in the same

individual. It is possible to obtain simultaneous recordings of pulsatility and ventilation of the same region of the lung.

The quantity of x rays needed for our method is one-tenth of the dosage required for standard fluoroscopy.

The pulsatility of the peripheral arterioles of the lung can also be recorded by the difference in density of the vessels in systole and diastole, and checked on the same graph with the electrocardiogram. The form and timing of aortic and cardiac transferred pulsations are different from those of the pulmonary vessels. An index of pulsatility can be calculated.

Accurate adjustment of the quantity of x rays falling on the photomultiplier has been obtained by special calibration, ensuring true comparisons.

It must be emphasized that these methods do not measure the volume of ventilation but the ratios between inspiration and expiration volumes. Similarly, the pulsatility of the vessels is measured but neither the volume nor the speed of the circulation. Within these limits the techniques are quick, accurate, and reliable.

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