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Research Article

THE PULSATILE NATURE OF THE PULMONARY CAPILLARY BLOOD FLOW *

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The nature of the pulmonary capillary blood flow is fundamental for the understanding both of pulmonary hemodynamics and of respiratory gas exchange. Direct examinations of the surface of the lung in the cat, rabbit, dog and rat (1–5) have indicated that pulmonary capillary blood flow is basically non-pulsatile. On the other hand, experimental studies by Lee and DuBois (6), using the body plethysmograph in man, have suggested that pulmonary capillary blood flow is consistently pulsatile. Their experimental evidence consisted of a rhythmic distortion of the record, synchronous with the heart beat, obtained during breathholding with open glottis, after a single inspiration of nitrous oxide.

However, since the first experiences with the pneumotachograph, it has been recognized that cardiovascular pulsations produce rhythmic changes of pressure in the conducting airways of the lungs. These rhythmic changes in intrapulmonary pressure are detected by the pneumotachograph through the changes in the rate of air flow which they produce. This phenomenon, illustrated in the pneumotachographic record of Figure 1, was recognized by Lilly (7) and designated by him as "cardiac air pulse." Subsequently, Bartlett, Brubach and Specht (8) found that rhythmic changes in the pneumotachographic record could be correlated with the pulsations observed in the plethysmographic pressure record obtained during breathholding after an inhalation of ambient air.

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In their original studies on the rate of pulmonary capillary blood flow by the plethysmographic method, Lee and DuBois (6) referred to "mechanical gas compression with the heart beat" to account for oscillations in the plethysmographic pressure record after a breath of ambient air. However, they invoked a completely different mechanism, i.e., the pulsatile uptake of nitrous oxide by blood perfusing the pulmonary capillaries, to account for similar, but larger, oscillations after a breath of nitrous oxide.

The present study was designed to distinguish between the role of pulsatile pulmonary capillary flow and the pulsations of the heart and great vessels in the genesis of the rhythmic distortions of the plethysmographic record.

SUBJECTS AND METHOD

Twenty-two tests were performed on 6 normal subjects. For each test, the subject was seated in an aluminum body plethysmograph which also contained a bag of the test gas. The gas in the bag was either 80 per cent nitrous oxide in oxygen, air, 100 per cent helium, or 100 per cent sulphur hexafluoride. Each subject inspired maxi-

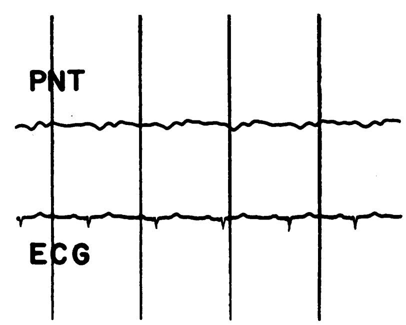

FIG. 1. PNEUMOTACHOGRAPHIC (PNT) AND ELECTROCARDIOGRAPHIC (ECG) TRACINGS OBTAINED FROM A NORMAL SUBJECT DURING BREATHHOLDING WITH THE GLOTTIS OPEN, AFTER A BREATH OF AMBIENT AIR. Rhythmic pulsations, related to the heart beat, are seen in the pneumotachographic record. The upward deflections of the pneumotachographic record represent expiratory flow.

mally from the bag after a maximum expiration and held his breath with mouth and glottis open for the next 20 to 30 seconds. In some instances the breathholding was also performed after a slight expiration following the maximal inspiration. During breathholding, the pressure in the plethysmograph and the electrocardiogram were recorded. The pressure was measured by an electronic system consisting of a Statham transducer (PL5TC-0.2-350), a SG-A-6 amplifier and an Electronics for Medicine oscilloscopic recording apparatus. The sensitivity of the system was such that the introduction of 100 ml of air into the plethysmograph produced a deflection of 25 mm in the record.

Each of the 6 subjects underwent at least three successive periods of breathholding using nitrous oxide, air and helium as test gases; 2 of the 6 underwent an additional period with sulphur hexafluoride as the inspired gas. Each subject performed this sequence 2 to 6 times. Each time the order of exposure to the different test gases was varied.

In order to relate the pneumotachographic pulsations to changes in intra-airway pressure, the closed system illustrated in Figure 2 was used. The system consisted of a 0.5 L bottle, a pneumotachograph and a rubber mouthpiece connected in series. The test gas was contained in a rubber bag which communicated with the mouthpiece through a two-way valve. By introducing a Statham transducer (P23-2D-250) it was possible to measure simultaneously the instantaneous variations in pressure and flow in this system and to record them with the electrocardiogram. The same respiratory maneuvers which were performed in the body plethysmograph were repeated using this system. The use of a bottle to record airway pressures had two advantages over the plethysmograph: *1*) the pressure variations were amplified considerably, and *2*) the effects of a change in body position on the contour of the pulsations could be assessed.

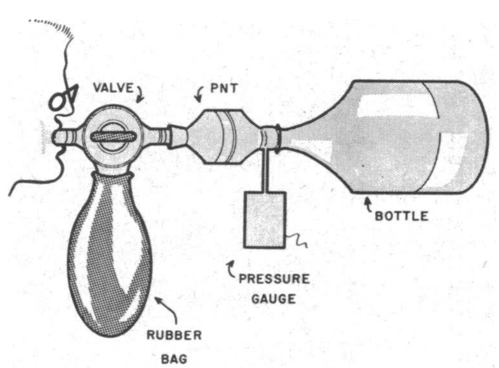

FIG. 2. SYSTEM USED FOR THE DETAILED ANALYSIS OF THE RELATIONSHIP BETWEEN THE CHANGES IN PRESSURE IMPOSED ON THE CONDUCTING AIRWAYS BY THE CARDIOVASCULAR PULSATIONS AND THE PULSATIONS SEEN IN THE PNEUMOTACHOGRAPHIC RECORD. The records obtained using this system are illustrated in Figure 7.

RESULTS

Figures 3, 4, 5 and 6 are records obtained during studies with the body plethysmograph. A typical tracing following a single breath of nitrous oxide appears as the left upper panel of Figure 3. This figure shows the electrocardiogram and the record of the changes of pressure with time during breathholding. It may be seen that: *1*) pressure within the plethysmograph falls gradually during breathholding; *2*) the gradual decline in pressure is rhythmically deformed by upward displacements of the baseline; *3*) the oscillations are synchronous with the heart beats; and *4*) each deflection reaches its peak approximately 0.2 of a second after the R wave of the electrocardiogram. The three other panels of this figure indicate that the rhythmic oscillations persist when air or even nonabsorbable gases are substituted for nitrous oxide. The different slopes with the different test gases are attributable to : *1*) the absorption of test gases such as nitrous oxide, by blood perfusing the pulmonary capillaries, *2*) the progressive warming of the plethysmograph by the patient, and *3*) the respiratory exchange ratio of the subject.

Similar tracings for three other subjects appear in Figure 4. This figure illustrates slight variations in the amplitude of the pulsations from subject to subject, and from gas to gas; for example, in Subjects E.B. and M.R. large oscillations occurred with all three gases; in the other subject, R.M., the oscillations were larger with nitrous oxide.

Figure 5 allows a closer examination of individual pulsations after a breath of nitrous oxide and of their relationships to the gradual decline in pressure. This figure shows that: *1*) the pressure falls in a straight line rather than in a stepwise manner, and *2*) the deflections are positive.

Figure 6 illustrates the effect of reversing the slope of the pressure curve on the nature of the deflections. The slope was reversed by a continuous inflow of oxygen into the plethysmograph after the subject had taken the breath of nitrous oxide. This device, which was used to remove the uncertainty of recognizing upward deflections from a falling baseline, emphasizes the positive nature of the deflections.

Except for minor variations, tracings identical to those of Figures 3, 4 and 5 were obtained from

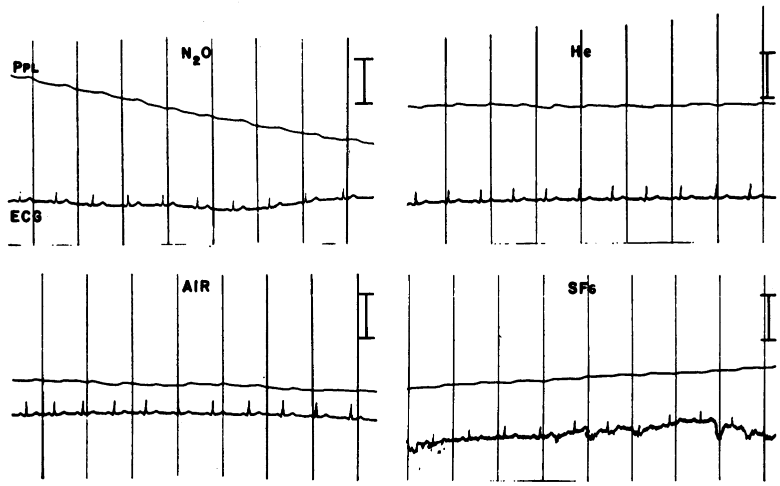

FIG. 3. PLETHYSMOGRAPHIC PRESSURE RECORD (P_{PL}) AND ELECTROCARDIOGRAM (ECG) OBTAINED FROM A NORMAL SUBJECT USING DIFFERENT TEST GASES. The gases were nitrous oxide (N_2O), helium (He), ambient air (air) and sulphur hexafluoride (SF_6). Similar types of rhythmic distortions of the pressure record are seen with all the test gases. The interval between the vertical time lines is 1 second. The vertical distance between brackets equals the deflection produced in the pressure record by the introduction of 100 ml of air into the body plethysmograph. The upward deflections of the pressure record represent an increase in pressure in the body plethysmograph.

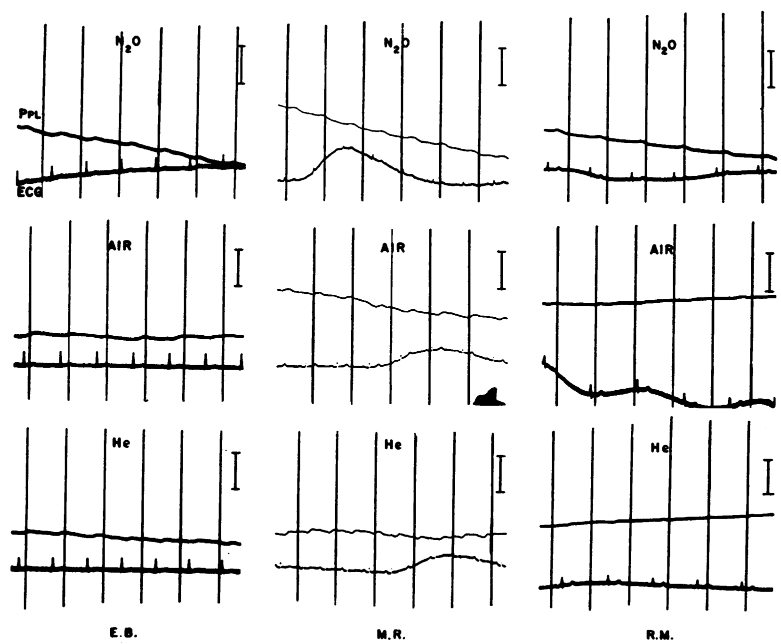

FIG. 4. PLETHYSMOGRAPHIC PRESSURE RECORDS (P_{PL}) AND ELECTROCARDIOGRAM (ECG) OF THREE NORMAL SUBJECTS. This figure illustrates the slight variations which are encountered in records from normal subjects using the different test gases. The time lines and the vertical distance between brackets are the same as those in Figure 3.

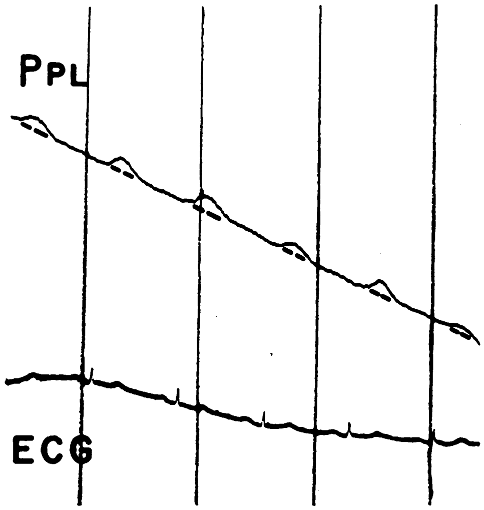

FIG. 5. PLETHYSMOGRAPHIC PRESSURE RECORD (P_{PL}) AND ELECTROCARDIOGRAM (ECG) FROM A NORMAL SUBJECT AFTER A BREATH OF NITROUS OXIDE. The slope of the pressure record follows a straight line which is periodically interrupted by upward displacements of the baseline synchronous with the heart beat. The time lines are the same as those in Figure 3. A vertical distance of 15 mm corresponds to the deflection produced in the pressure record by the introduction of 100 ml of air into the body plethysmograph.

all subjects. The patterns were not altered appreciably by the level of the inspiratory capacity at which breathholding was performed. As a rule, slight variations in amplitude occurred during successive exposures of a subject to the same test gas. Moreover, in five of the six subjects, the size of the pulsations with the different test gases varied unpredictably; only in Subject R.M. (Figure 3) were larger pulsations observed consistently with nitrous oxide than with air or helium. No correlation could be made between the density of the gas inspired and the contour of the plethysmographic pressure record.

An attempt was made to assess the effects of closing the mouth and nose (and glottis) on the pressure record. Both air and nitrous oxide were used as test gases. This maneuver was found to have no effect on the slope of the pressure curve but did diminish the amplitude of the pulsations.

Figure 7 illustrates the results obtained by the system of Figure 2. It can be seen that the rhythmic distortions in the pneumotachographic records are synchronous with those in airway pressure.

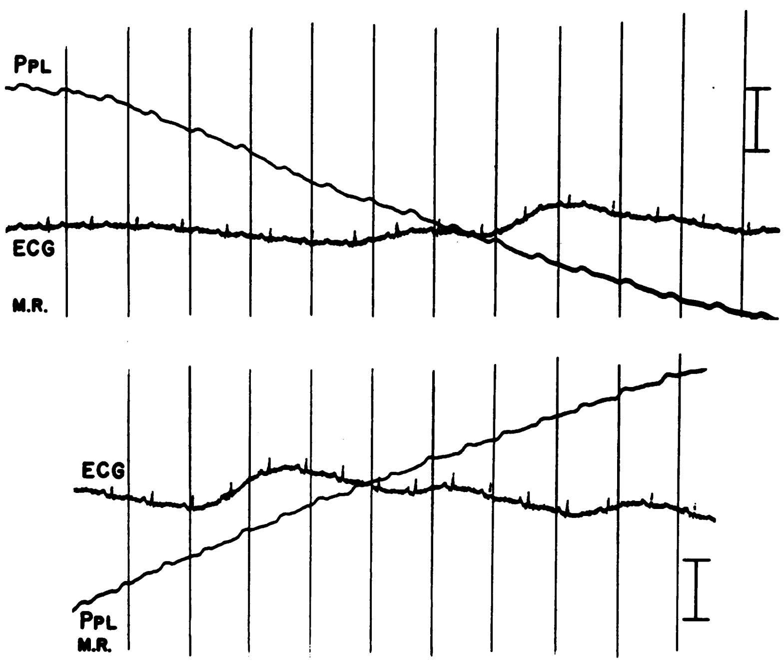

FIG. 6. PLETHYSMOGRAPHIC PRESSURE RECORDS (P_{PL}) AND ELECTROCARDIOGRAMS (ECG) FROM A NORMAL SUBJECT AFTER A BREATH OF NITROUS OXIDE. The upper half of the figure shows the usual plethysmographic record. The lower half shows a plethysmographic record the slope of which was artificially reversed to emphasize the positive nature of the deflections. The time lines and the vertical distance between brackets are the same as those in Figure 3.

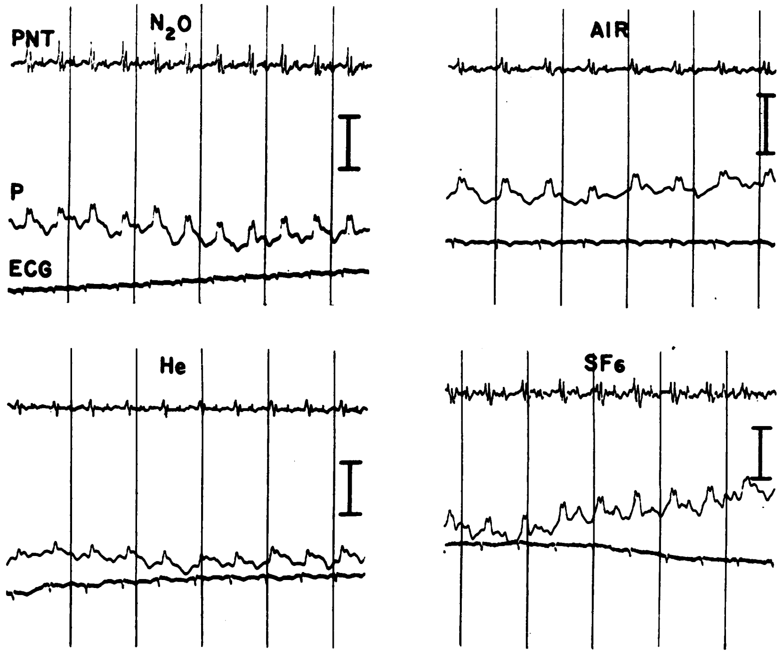

FIG. 7. PNEUMOTACHOGRAPHIC (PNT), PRESSURE (P) AND ELECTROCARDIOGRAPHIC (ECG) TRACINGS OBTAINED FROM A NORMAL SUBJECT, DURING BREATHHOLDING, USING THE SYSTEM ILLUSTRATED IN FIGURE 2. The test gases included nitrous oxide (N_2O), ambient air (air), helium (He) and sulphur hexafluoride (SF_6). Each record illustrates the interdependence of the pneumotachographic and the pressure pulsations and the electrical events of the cardiac cycle. There is a delay of 0.02 of a second between the deflections in the pneumotachographic record and the corresponding deflections in the pressure tracing. This delay arises from the different locations of the pneumotachograph and the pressure gage in the lung-bottle system (see Figure 2). Time interval between the vertical time lines is 1 second. The vertical distance between brackets equals the deflection produced in the pressure record by the introduction of 50 ml of air into the system. The upward deflections of the pneumotachographic record represent expiratory flow. The upward deflections of the pressure record represent an increase in pressure in the system.

Not illustrated is the fact that while changes in the body position of the patient do elicit changes in the pneumotachographic and pressure pulsations, they do not affect their temporal relationships to the cardiac cycle as recorded by the electrocardiogram. It should also be noted that the pressure tracings obtained from the lung-bottle system are not influenced by the same factors which determine the slope of the plethysmographic pressure records, i.e., the absorption of gas by pulmonary blood, changes in the temperature of the body plethysmograph and changes in the subject's respiratory exchange ratio. In the lung-bottle system, changes which these factors produce in the volume of gas are adjusted by automatic adaptations of the chest cage which the system is not equipped to detect.

DISCUSSION

The results indicate that the rhythmic oscillations in the plethysmographic pressure record after a single breath of nitrous oxide reflect transmission of the pulsations of the heart and great vessels rather than variations in the rate of absorption of nitrous oxide by a pulsatile pulmonary capillary blood flow.

This conclusion is supported by a consideration of the two likely mechanisms by which such oscillations could be produced:

1. If the pulsations after nitrous oxide do reflect variations in the rate of nitrous oxide uptake by pulsatile capillary flow, the records would be expected to have the following characteristics: *a*) The deflections should vary according to the absorbability of the test gas; with nitrous oxide, a negative deflection should be observed every time a blood pulse wave reached the pulmonary capillary bed; conversely, with air or nonabsorbable gases, deflections should be negligible or absent. *b*) The pattern of the pressure record obtained after a breath of nitrous oxide should differ from the pattern obtained after a breath of the other test gases; after nitrous oxide, the pressure should drop in a stepwise manner, with the fall accentuated every time a pulse of blood reached the pulmonary capillary bed; after air or the nonabsorbable gases, the pressure should follow an essentially straight line. As illustrated in Figures 3, 4, 5 and 6, none of these predictions was fulfilled.

2. On the other hand, if the pulsations arise from the impacts of the heart and great vessels, they should: *a*) occur with all test gases, and *b*) be synchronous with cardiac systole. That these conditions are fulfilled is indicated in Figures 3, 4 and 5 by the similarity in tracings obtained with the different test gases and by the relationships of the deflections to cardiac systole, i.e., their occurrence during the period of ventricular ejection (9).

Accepting the origin of the plethysmographic pressure pulsations in cardiovascular impacts, the prospect arises that variations in the amplitude of the pulsations during successive tests may result from either variation in the stroke volume of the heart or in different degrees of opening of the glottis; on the other hand, slight changes in pattern of the plethysmographic pulsations may arise from slight shifts in the position of the patient.

The data obtained in this study indicate that the pulsations in the plethysmographic record share a common origin with those in the pneumotachographic record. In both instances, the pulsations seem to arise from changes in pressure in the conducting airways produced by the mechanical events associated with cardiac systole.[1] As expected, the contour of the pulsations is somewhat different in the two types of records on at least two accounts: *1*) the plethysmograph measures changes in pressure directly, whereas the pneumotachograph measures such changes indirectly by the changes in flow which they produce; and *2*) the amplitude of the pulsations in the pneumotachographic record varies with the rate of change in pressure, whereas their amplitude in the plethysmographic record depends solely on the magnitude of the change.

It must be emphasized that the results reported in this paper do not pertain to the method proposed by Lee and DuBois for the measurement of the *mean* pulmonary capillary blood flow, i.e., the cardiac output (6). This measurement depends on the *mean* slope of the plethysmographic pressure record and is independent of any peculiarities in the contour of this record. On the other hand, their calculated values for the rate of "instantaneous" pulmonary capillary blood flow are certainly open to question since such calculations depend on the concept that the pulsations in the plethysmographic pressure record reflect a pulsatile uptake of nitrous oxide. This premise is not supported by the results of the present study.

In conclusion, the present study indicates that

[1] In spite of the convincing evidence that the cardiovascular pulsations produce rhythmic changes in pressure in the body plethysmograph, the mechanism by which such changes are produced is not completely understood. Since blood and tissues are incompressible, their simple displacement by the mechanical effects of cardiac systole would not give rise to changes in pressure in the plethysmograph. The data obtained in this study are consistent with the view that the systolic impacts affect the plethysmograph by way of the conducting airways either directly, by displacing pulses of air into and from the plethysmograph (when the mouth and glottis are open), or indirectly through rhythmic displacements of the chest wall.

Several different factors, operating singly or together, may be involved in the production of changes in pressure in the conducting airways during cardiac systole. These include: *1*) the different elastic properties of the body structures and of the air affected by the impacts, *2*) the resistance of the airways to the displacement of the air mobilized by these impacts, and *3*) the momentary imbalance between the thoracic inflow and outflow of blood during cardiac systole.

Bartlett and co-workers (8) have proposed that the momentary imbalance between thoracic inflow and outflow of blood, in conjunction with the peripheral arterial pulsations produced by the displaced blood, is responsible for the rhythmic changes in the plethysmographic pressure.

The present study does not permit distinction between the relative roles of these different factors.

the pulsations seen in the plethysmographic pressure record after a breath of nitrous oxide are due to mechanical transmission of the pulsations of the heart and great vessels and cannot be used as evidence for a pulsatile pulmonary capillary blood flow.

SUMMARY

1. The nature of the pulmonary capillary flow in man has been investigated using the body plethysmograph and various test gases.

2. Rhythmic oscillations in the plethysmographic record during breathholding with glottis open were shown to be synchronous in time with the cardiac cycle and to occur regardless of the density of the gas or its solubility in blood.

3. The rhythmic oscillations in the plethysmographic record were also shown to be synchronous with those in the pneumotachographic record.

4. Evidence is presented to indicate that both the plethysmographic and pneumotachographic records have a common origin in the mechanical events of the cardiac cycle rather than in the uptake of the test gas by pulsatile pulmonary capillary flow.

5. The conclusion is reached that the pulsations in the plethysmographic record cannot be used as evidence that pulmonary capillary flow is pulsatile.

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