DETERMINATION OF LUNG CLOSING VOLUMES BY CAPNOGRAPHY AND NITROGRAPHY

PHASE V ON THE SINGLE BREATH CURVE

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A new method of determining closing volumes (CV) by single breath capnography is suggested. CV obtained by capnography agree with results obtained by nitrography. Calculation of indices of expiratory closing of the respiratory passages (ECRP) for 70 patients showed that the frequency of recording of CV by capnography and nitrography does not differ significantly at the P = 0.95 level. A phase V, not previously observed, was distinguished on the single breath curve. Whereas phase IV indicates the beginning of ECRP, phase V indicates complete closing of the respiratory passages at the base of the lungs. Complete closing of the respiratory passages at the base of the lungs takes place on average after expiration of 0.54 liter of air from the time when closing of the respiratory passages begins.

KEY WORDS: single breath curve; closing of the respiratory passages; closing volume; phase IV of expiration; phase V of expiration.

Three phases can be distinguished on the single breath curve (SBC). In single breath nitrography, after inhalation of pure oxygen (O_2) they have the following appearance: Phase I [the nitrogen (N_2) concentration close to zero] corresponds to gas leaving the dead space of the respiratory passages; phase II (a rapid rise in the N_2 concentration) is mainly due to the absence of any marked difference in concentration of the gas between the dead space and the alveolar region of the lungs; phase III (the so-called alveolar plateau, which may have a considerable slope, in patients with diseases of the lungs, for example) is due to gas leaving the alveolar region of the lungs.

Not very long ago phase IV was distinguished visually in the alveolar region of SBC, as a deviation away from the initial slope of the "alveolar plateau" [1-9]. The beginning of deviation of phase IV from phase III is considered to correspond to the beginning of expiratory closing of the respiratory passages (ECRP). The maximal expiratory volume corresponding to phase IV is called the closing volume (CV) of the lungs. Other indices of ECRP which are derivatives of CV and other lung volumes also are used.

In this paper a new method of determining CV by the use of the CO_2 analyzer of the capnography is suggested. Analysis of the course of the single breath capnograms and the corresponding dynamics of cardiogenic fluctuations of gas composition on the SBC revealed a separate phase V and indicated its physiological basis.

EXPERIMENTAL METHODS

Indices of ECRP were obtained by means of a capnograph, nitrograph, and spirograph from Godart, the Netherlands. The CV was obtained by capnography, and in the same way by nitrography, as follows. The patient inhaled 1.5-2 liters of air (or O_2) and, after holding the breath for 10-15 sec, breathed out slowly to the level of the residual volume (RV) of the lungs under the bell of the spirograph, into which the mixture analyzed by the gas analyzer also was introduced. During single breath nitrography, the breath was not held except when the nitrogram and capnogram were recorded simultaneously after inhalation of O_2 (see below). The capnogram (nitrogram) and spirogram were thus recorded simultaneously. Five phases were distinguished on the resulting SBC, as illustrated in Fig. 1a.

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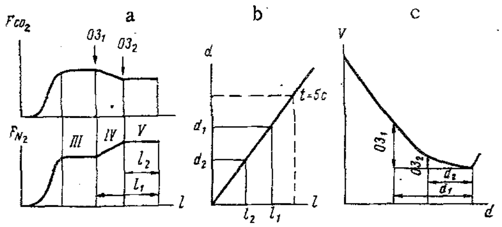

Fig. 1. Determination of CV_1 and CV_2 from the capnogram (nitrogram, a) and spirogram (c) of the same breath by means of a correlation graph (b) between displacement of the capnograph (nitrograph) tape (abscissa, l) and the spirograph tapes (ordinate, d). Here and in Fig. 2, arrows on SBC indicate points determining CV_1 and CV_2.

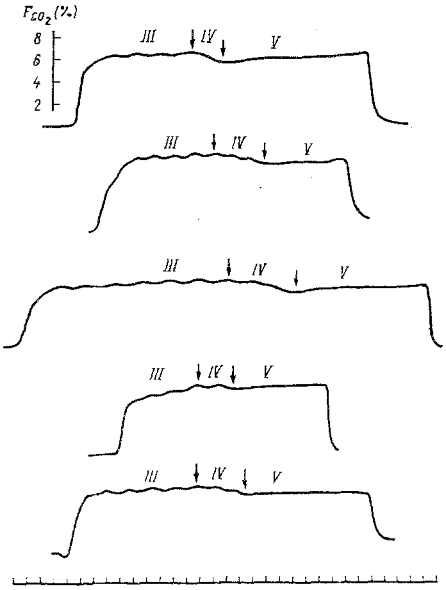

Fig. 2. Single breath capnograms obtained for five sitting patients, with indication of phases III, IV, and V.

To compare the spirogram and capnogram (nitrogram) a parametric graph (Fig. 1b) was plotted to show movement of the spirograph and capnograph (nitrograph) tapes as a function of time. Displacement of the spirograph tape during a definite time, for example 5 sec, was plotted along the ordinate and displacement of the capnograph (nitrograph) tape during the same time on the abscissa. A straight line was drawn through the point with the coordinates thus obtained and the origin, to show the relationship between displacements of the tapes of the two instruments. From displacements of the capnograph (nitrograph) tape corresponding to phases IV and V the corresponding displacements of the spirograph tape were obtained, after which the volumes themselves were found by means of the expiration spirogram: CV_1 corresponding to phases IV and V (phase IV in the old notation [1-9]), and CV_2, corresponding to phase V (Fig. 1).

To determine the significance of the results obtained by capnography, CV_1 and CV_2 were determined for 10 patients by capnography and nitrography simultaneously. The instruments were connected together so that the capnogram, nitrogram, and spirogram were recorded simultaneously for the same breath after inhalation of 1.5-2 liters O_2 and breath holding for 10-15 sec.

Indices of ECRP for 70 patients also were determined by capnography and nitrography consecutively. For each patient it was noted whether CV was recorded either by one instrument or by both instruments to-

TABLE 1. Mean Indices of ECRP and Alveolar Gradients Corresponding to Phases III, IV, and V on the Single Breath Nitrogram

	Age of subjects	CV_1, %	CV_2, %	ΔCV, liters	CC_1, %	CC_2, %	$\Delta F/\Delta V_{III}$	$\Delta F/\Delta V_{IV}$	$\Delta F/\Delta V_V$
							vols., %/liter		
M	53,8	24,85	10,66	0,54	48,83	39,75	5,33	11,3	1,97
min	37	9,4	1,24	0,30	29,5	21,1	2,03	4,5	0,0
max	76	45,4	24,0	1,00	72,5	62,0	13,3	27,3	12,5
σ	8,0	7,17	4,66	0,19	8,64	8,27	2,3	4,84	2,4
Δ	1,9	1,72	1,13	0,27	1,13	2,09	2,0	0,56	0,58

gether; CV_1 and CV_2 and the slopes of the SBC corresponding to phases III, IV, and V: $(\Delta F/\Delta V)_{III}$, $(\Delta F/\Delta V)_{IV}$, $(\Delta F/\Delta V)_V$; also were determined from the single breath nitrogram. The values of RV and other spirometric indices required for calculation of the closing capacity (CC) also were found: $CC_1 = RV + CV_1$, $CC_2 = RV + CV_2$, and CV was expressed as a ratio of the vital capacity (VC) and CC as a ratio of the total capacity (TC) of the lungs.

EXPERIMENTAL RESULTS AND DISCUSSION

In man in a vertical position, inequalities of ventilation and blood flow are known to exist and are such that ventilation of the apical regions is less than the basal regions; for the blood flow the difference is more marked still [10]. Differences in N_2 concentration in the apical and basal regions of the lungs after inhalation of O_2 are mainly determined by inequality of ventilation. Differences in the CO_2 concentration after breath holding for 10-15 sec are mainly due to inequality of perfusion, for during this time the CO_2 concentration in the basal regions of the lungs approximates to that in venous blood, whereas in the apical regions it will be smaller because of both the reduced blood flow and the increased RV for these regions compared with the basal. On single breath capnograms it was therefore possible to distinguish phases connected with ECRP (Fig. 2).

Marked cardiogenic fluctuations in the concentration of the test gas were observed on the capnograms (and to a much lesser degree on the nitrograms). They can perhaps be explained on the grounds that gas from the basal parts enters the mixed expired gas unequally during systole and diastole because of mechanical effects of the heart on the lungs. During diastole the heat accelerates the relative contribution of these regions to the total expired volume. During systole the heart reduces the outflow of gas, and may even draw a certain volume of gas into these regions during expiration at slow speeds.

A number of actual capnograms are shown in Fig. 2. The relatively uniform alveolar slope of phase III decreases with the onset of phase IV. This is explained by the beginning of expiratory closing of the basal segments of the lungs. Later, after a comparatively rapid change in the CO_2 concentration in phase IV, a new relatively stable gradient is established in phase V. How can the onset of phase V be explained? What is the physiological state of the lungs under these circumstances? Some help with the answers to these questions is given by the behavior of cardiogenic fluctuations in the gas composition during the change from one phase to another.

With the onset of phase IV, the previously relatively constant fluctuations in CO_2 concentration begin to diminish rapidly in amplitude in the course of expiration. This fact indicates that during phase IV the respiratory passages of the basal segments of the lungs gradually become constricted and closed; they continue to make a contribution to the concentration of the mixed expired gas, but that contribution decreases as expiration continues. A characteristic of phase V is that with its onset the cardiogenic fluctuations of gas composition often disappear completely on the SBC obtained both by capnography and by nitrography. This means that during phase V gas is exhaled purely from the apical segments. The absence of fluctuations indicates that the respiratory passages of the basal segments are completely closed, and even the force of the heart during diastole, leading to additional compression of the basal segments of the lungs, does not cause the corresponding respiratory passages to open. The very small cardiogenic waves that sometimes persisted during phase V were explained in these cases by differences in perfusion of the apices of the patient's right and left lungs and by the greater force of the mechanical impulses of the heart on the left than on the right lung.

Does further closing of the respiratory passages take place during phase V of expiration? In healthy subjects there is more reason to consider that it does not, for such moments are considered not to arise for the middle and apical regions of the lungs during expiration as far as RV [8]. But even if this process does take place, closing will be much slower than for the basal regions of the lungs because of the lesser predisposition of the apical regions of the lungs to close and because of the smallness of the expiratory volumes corresponding to phase V.

Values of CV were determined for 10 patients by capnography and nitrography synchronously. The values of CV determined by the two methods were found to be equal regardless of how they were obtained. The method of single breath capnography was thus shown to be adequate for quantitative assessment of ECRP indices.

CV was determined in 70 patients both by capnography and by nitrography, and a CV was found in all subjects. In five patients, however, CV was recorded only on the nitrograms and in another three patients only on capnograms. By calculating the frequency of recording of CV by the two instruments (67/70 and 65/70 respectively) and by determining the significance of their difference, it was found that the frequencies of recording CV with a probability of 0.95 do not differ significantly according to the experimental data. Capnography thus affords virtually the same opportunities for determination of CV as nitrography.

Mean values (M) for the following indices of ECRP are given in Table 1: CV_1 and CV_2 as percentages of VC, CC_1 and CC_2 as percentages of TC, $\Delta CV = CV_1 - CV_2$, in liters, gradients of SBC corresponding to phases III, IV, and V and expressed as the N_2 concentration in volumes %/liter of the expired mixture, and also the age of the subjects. Minimal and maximal values (min, max), the standard deviation σ, and half of the confidence interval Δ, $P = 0.95$, are stated for each index. These results were obtained by analysis of single breath nitrograms of 69 patients with bronchopulmonary pathology. The gradient of phase IV, $\Delta F/\Delta V_{IV}$, characterizing the speed of closing of the respiratory passages, was always greater than the gradient of phase III, and the gradient of phase V was considerably less than that of phase IV. Complete closure of the respiratory passages of the lower segments of the lungs occurred on average after exhalation of 0.54 liter of air from the moment of beginning of ECRP.

In the presence of considerable disturbances of ventilation, when marked laminar nonhomogeneities of gas composition are present in the lungs, the beginning of phase IV is difficult to identify, whereas phase V is more easily detected in such situations. This fact can be regarded as a slight advantage of CV_2 and CC_2 as indices compared with CV_1 and CC_1, for if it is difficult to find the beginning of ECRP, it thereby becomes important to find a value characterizing the state of complete closure of the respiratory passages of the basal segments of the lungs.

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