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THE VARIATIONS IN INTRA-ABDOMINAL PRESSURE AND THE ACTIVITY OF THE ABDOMINAL MUSCLES DURING BREATHING; A STUDY IN MAN

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The muscles of the antero-lateral abdominal wall are thought to aid expiration by pulling the costal margin downwards and by raising the intra-abdominal pressure. These muscles have been studied electromyographically (Campbell, 1952; Campbell & Green, 1953) in young subjects in the supine position. It has been found that, during increasing pulmonary ventilation, (1) the muscles only come into action when the pulmonary ventilation has increased to a considerable extent, and the activity occurs towards the end rather than at the beginning of the expiratory phase; (2) the force of contraction of these muscles as judged from the electromyographic records is small compared with the force produced when performing static expiratory efforts, and very small compared with that produced during voluntary movements. In view of these findings it was decided to investigate whether the muscles of the antero-lateral abdominal wall do in fact aid expiration by raising the intra-abdominal pressure.

The pressure may be measured at various sites in the abdomen, and absolute values will depend on the site chosen. The intra-gastric pressure was selected for two reasons. First, access is easy; second, the stomach is situated immediately under the left dome of the diaphragm close to the costal margin, and respiratory variations in intra-abdominal pressure probably affect it moıe than most other abdominal organs.

Very occasionally slow rises and falls of the intra-gastric pressure were encountered which may have been due to variations in the tone of the gastric musculature. The greatest rise recorded was to 33 cm H_2O. Since the rate of rise and fall was slow compared with the superimposed respiratory changes no interference with the experiments resulted.

METHODS

Intra-gastric pressure. A flaccid balloon (vol. 17 ml.) was connected through a rubber tube (2 mm internal diameter) to an inductance manometer which was arranged to give a record through one of the pens of an Ediswan ink-writer. On one occasion simultaneous records were taken with the inductance manometer and a Hansen capacitance manometer (Hansen, 1949); the records were identical.

The balloon and tube were passed via the nose and subsequently swallowed. In subjects who could not pass the tube through the nose, the tube was swallowed via the mouth and brought out at the side of the mouth-piece. The system was filled with air. The range of pressure recorded was 0–50 cm H_2O.

The electromyogram (e.m.g.). The e.m.g. of the right external oblique was obtained with surface electrodes and an Ediswan 4-channel oscillograph as described previously (Campbell & Green, 1953).

Respiration. Respiration was recorded on the electromyograph paper with a writing point attached to a Kendrick 6 l. spirometer. The respiration trace was ahead of the manometer and e.m.g. traces by a distance corresponding to $\frac{1}{7}$ sec in the published records.

The subjects were nine healthy men aged 18–27. They were examined in the supine position.

RESULTS

Quiet breathing

The electromyogram showed no detectable muscular activity. The intra-gastric pressure at the end of a quiet expiration was 5–15 cm H_2O above atmospheric pressure. In most subjects there was a slight respiratory variation which took the form of a rise during inspiration and a fall during expiration. The overall variation was no more than 3–5 cm H_2O.

The effects of progressively increasing pulmonary ventilation

The subjects rebreathed from the 6 l. spirometer with no CO_2 absorber in the circuit. They were, therefore, subjected to both CO_2 excess and O_2 lack. Before they became distressed they were encouraged to increase the volume of their breathing voluntarily to the order of 100 l./min.

In all subjects the records showed three phases:

Phase (1) (see Fig. 1). During this phase there was no detectable muscular activity. The variation in the intra-gastric pressure was of the same pattern as that occurring during quiet breathing. On occasions the magnitude of the variation increased but it rarely exceeded 10 cm H_2O.

Phase (2) (see Fig. 2). Activity appeared in the muscles during expiration. The intra-gastric pressure showed the usual increase during inspiration, but in addition a slight rise in pressure occurred during expiration. During this phase the maximum pressure developed during expiration did not exceed that developing during inspiration.

Phase (3) (see Fig. 3). As the ventilation increased the muscular activity during expiration increased. Phase (3) occurred when the intra-gastric pressure

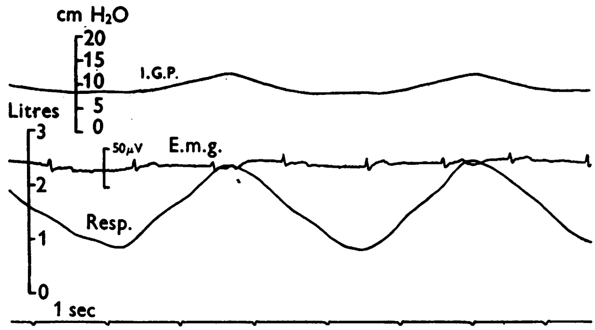

Fig. 1. Progressively increasing pulmonary ventilation. Subject M. Ca., supine. Records from above downwards: I.G.P., intra-gastric pressure; e.m.g., electromyogram from the right external oblique muscle; resp., respiration (inspiration upwards). Time in seconds. The record was taken 1 min after the subject began to re-breathe expired air from the spirometer and pulmonary ventilation had increased to 27 l./min.

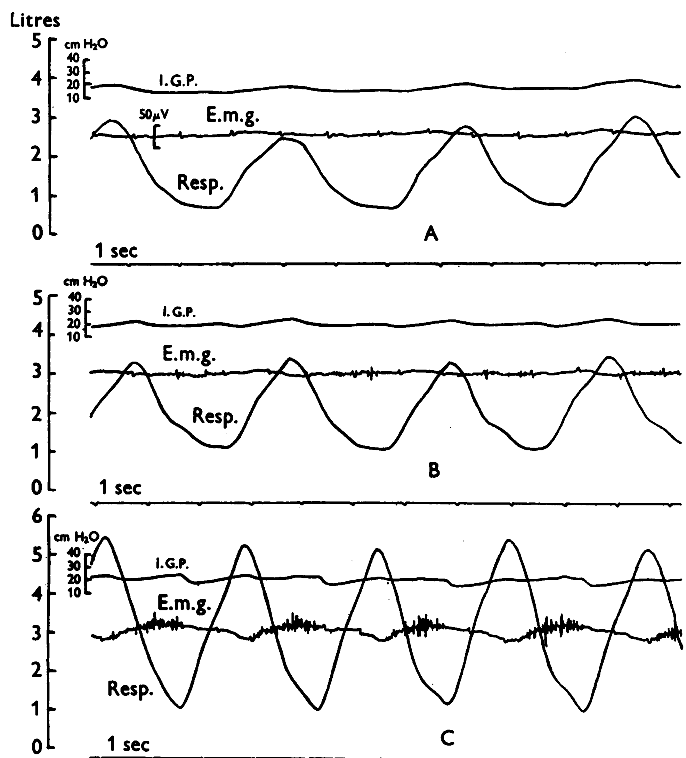

Fig. 2. Progressively increasing pulmonary ventilation. Subject M.Ca., supine. Records as in Fig. 1. Note that the intra-gastric pressure scale is different from that in Fig. 1. A, the record 2½ min after the subject began to rebreathe expired air from the spirometer (pulmonary ventilation 34 l./min); B, 12 sec after A (pulmonary ventilation 42 l./min); C, 120 sec after B (pulmonary ventilation voluntarily increased to 96 l./min).

at the end of expiration had become greater than that at the end of inspiration. We term this change 'reversal'. Commencing 'reversal' is shown in some of the breaths of Fig. 2C and strikingly in the latter part of Fig. 3.

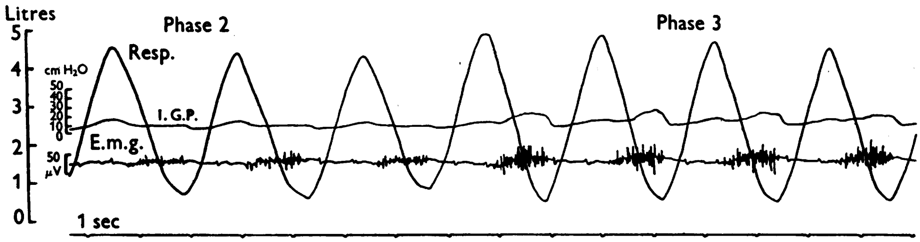

Fig. 3. Progressively increasing pulmonary ventilation. Subject M.Ca., supine. Records from above downwards: resp., respiration (inspiration upwards); I.G.P., intra-gastric pressure; e.m.g., electromyogram from the right external oblique muscle. Time in seconds. This record is taken from a similar experiment to that reproduced in Fig. 2. The subject was voluntarily increasing his pulmonary ventilation from 94 l./min at the beginning of the record to 108 l./min at the end. The last four breaths show 'reversal'.

TABLE 1. The pulmonary ventilation at which (*a*) muscular activity was first detected, and (*b*) 'reversal' occurred

	Ventilation rate (l./min)	
Subject	(*a*) Activity first appeared	(*b*) Reversal
M.Ch.	47	159
J.Hu.	57	123
W.L.	37	92
M.G.	39	84
G.M.	32	78
D.A.	100	108
J.Ho.	71	104
J.Da.	26	74
M.Ca.	34	101
Mean	49	102

TABLE 2. Total respiratory variation in intra-gastric pressure at two levels of ventilation

	No. of subjects	
Intra-gastric pressure (cm H_2O)	40 l./min	70 l./min
Less than 5	5	3
5–10	3	5
10–15	1	1

Table 1 shows the pulmonary ventilation at which the change from phase (1) to phase (2) occurred and the level of ventilation at which the change from phase (2) to phase (3) in intra-gastric pressure occurred (i.e. 'reversal'). These results show a wide variation from subject to subject, but the minimum pulmonary ventilation at which 'reversal' occurred was high (74 l./min). In all subjects 'reversal' occurred at a higher pulmonary ventilation than did the onset of muscular activity.

Table 2 shows how small are the changes in intra-gastric pressure. In only one of the nine subjects did the total variation exceed 10 cm H_2O.

The effect of maximal voluntary breathing

Fig. 4 shows the effect of this manoeuvre when carried out by the same subject who provided the previous figures. Vigorous contraction of the abdominal muscles occurred throughout each expiration. The intra-gastric pressure rose abruptly to over 50 cm H_2O at the beginning of each expiration and fell abruptly at the beginning of inspiration. By voluntary control the subjects could progress gradually to this type of breathing, but a marked rise in the intra-gastric pressure during expiration never occurred in the absence of voluntarily controlled breathing. This type of breathing never occurred in the involuntary respiration of asphyxia, even though the subjects became cyanosed and distressed.

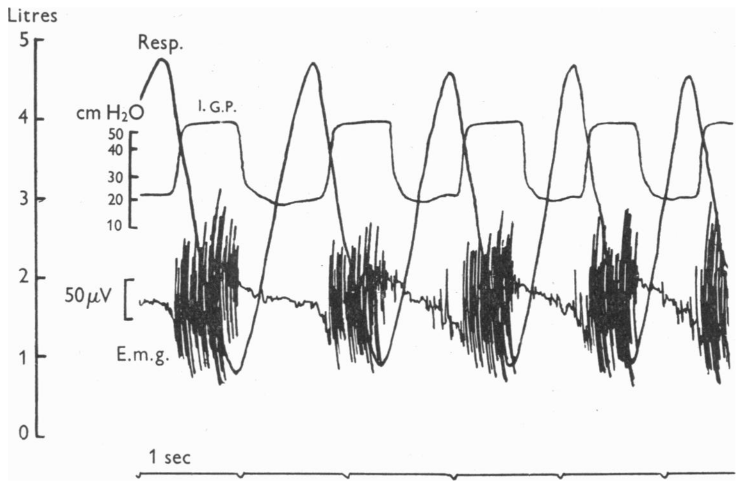

Fig. 4. Maximal voluntary breathing. Subject M. Ca., supine. Records as in Fig. 3. The pulmonary ventilation is 190 l./min (the flat top of the I.G.P. record is due to the recording pen reaching the limit of its sweep).

The effect of static expiratory efforts (*Fig.* 5)

Static expiratory efforts were performed as described by Campbell & Green (1953). The subjects maintained an expiratory pressure by centring the needle on a differential manometer which had been displaced by a predetermined pressure. The efforts were made at the end of a quiet expiration, i.e. at the resting respiratory level, when the relaxation pressure of the chest and lungs is zero. Eight subjects were studied. In all subjects the intra-gastric pressure exceeded the expiratory effort. In seven, expiratory efforts of 10–40 cm H_2O produced intra-gastric pressures exceeding the expiratory effort by 5 cm H_2O. In two of the subjects the expiratory efforts of 30 and

40 cm H_2O caused the intra-gastric pressure to rise to between 10 and 20 cm H_2O above the expiratory effort.

One subject developed high and variable intra-gastric pressures whenever he made an expiratory effort. We think that he was expiring not only against the resistance but also against his closed glottis.

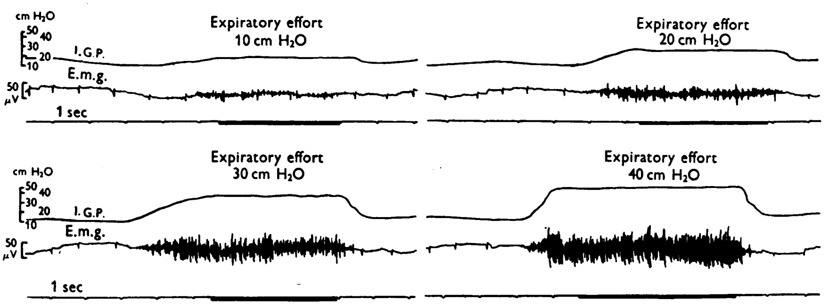

Fig. 5. The effect of static expiratory efforts. Subject W. L., supine. Records from above downwards: I.G.P., intra-gastric pressure; e.m.g., electromyogram from the right external oblique muscle. Time in seconds and signal. For the duration of each signal the subject was maintaining a constant expiratory effort. His chest was at the resting respiratory level.

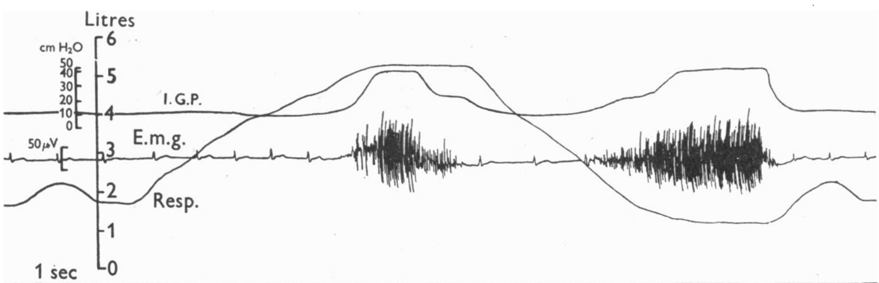

Fig. 6. Maximal inspiration followed by maximal expiration (vital capacity). Subject G.M., supine. Records as in Fig. 1 (the flat top to the I.G.P. record is due to the recording pen reaching the limit of its sweep).

The effect of a maximal inspiration followed by a maximal expiration (Vital Capacity test)

Fig. 6 shows a typical record of such a manoeuvre. Our findings were similar to those of Mills (1950). A rise in intra-gastric pressure occurred at the end of inspiration which was associated with a burst of activity in the muscles. With the onset of expiration the intra-gastric pressure fell until the expulsion of the expiratory reserve volume began when there was a marked rise in intra-gastric pressure and considerable muscular activity. The maximum pressure developed was over 50 cm H_2O. Mills (1950) gives a range of 57–183 mm Hg (77–250 cm H_2O).

The effect of coughing

Fig. 7 is a record showing a series of three coughs. A single cough produced a sudden rise in intra-gastric pressure and a burst of muscular activity which varied with the force of the cough. Even a moderate cough caused a rise of pressure to 40–50 cm H_2O.

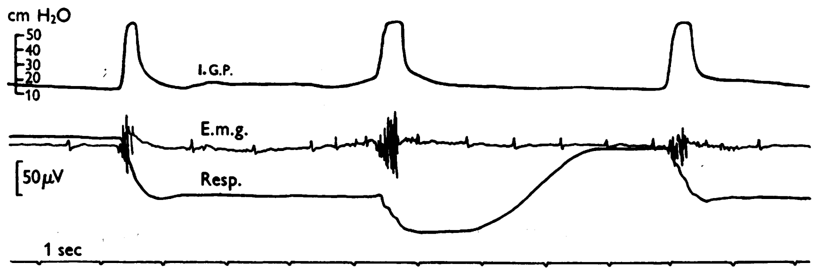

Fig. 7. The effect of coughing. Subject J.Ho., supine. Records as in Fig. 1. This record shows three short coughs. Each of them produces a burst of muscular activity and a sharp rise in intra-gastric pressure.

DISCUSSION

The experiments were performed with the subjects supine because we wished to minimize the effects of gravity and posture upon the abdomen. The static expiratory effort experiments show that at the resting respiratory level, when the relaxation pressure of the chest wall and lungs is zero, an intra-pulmonary pressure cannot be developed by the respiratory muscles without a greater pressure occurring in the stomach. On anatomical grounds it appears unlikely that the muscles of expiration can develop intra-pulmonary pressures without there being some rise of intra-abdominal pressure. If the muscles of expiration were confined to the thorax this rise in intra-abdominal pressure would not exceed the intra-thoracic pressure. Our findings show that the intra-abdominal pressure under these conditions exceeds the intra-thoracic pressure and, therefore, suggest that the abdominal muscles are the important muscles of static expiratory effort.

During quiet respiration and phase (1) of the rebreathing experiments the intra-gastric pressure rises on inspiration and falls during expiration. There is no contraction of the abdominal muscles; the rise in intra-gastric pressure is due to the compression of the abdominal viscera by the descending diaphragm. The overall variation of 3–5 cm H_2O corresponds to the variation in intra-abdominal pressure which occurs with the phases of respiration in an artificial pneumoperitoneum.

The rise in intra-abdominal pressure during inspiration will aid the following expiration. However, the rise in pressure is small. It increases only slightly as the volume of ventilation increases. This is because of the distensibility of the abdomen which bulges forwards and laterally. Also some of the increased tidal volume is obtained by an increase in costal breathing.

As the pulmonary ventilation increases, contraction of the abdominal musculature occurs in late expiration. The changes in intra-gastric pressure due to this contraction are slight. During phase (2) the pressure developed during expiration does not exceed that at the end of inspiration. The part played by the abdominal musculature in actively aiding expiration by raising intra-abdominal pressure is, therefore, small. It is not until a pulmonary ventilation of 74–159 l./min is reached that 'reversal' occurs, and the intra-gastric pressure during expiration exceeds that during inspiration (phase 3). Even now the expiratory pressure rise is not large, and is occurring only towards the end of expiration. We did not observe 'reversal' in the absence of voluntary effort, but it is possible that it occurs at the higher levels of exercise ventilation.

During maximum voluntary ventilation, on the other hand, the intra-abdominal pressure no longer remains relatively constant; the abrupt rise in intra-abdominal pressure at the beginning of each expiration will actively force the diaphragm upwards.

The vital capacity test shows that expiration exceeding the resting respiratory level (i.e. decrease of the expiratory reserve volume) is associated with the contraction of the abdominal muscles and a rise in intra-gastric pressure.

In the erect posture the relaxation pressure at any lung volume is less than in the supine (Rahn, Otis, Chadwick & Fenn, 1946). It would be expected, therefore, that muscular contraction sufficient to produce 'reversal' would occur at a lower level of ventilation. Preliminary experiments have, in fact, shown this to be so: in four subjects the pulmonary ventilation at which 'reversal' occurred was 55–95 l./min. This is still a volume of breathing adequate for most forms of exercise.

SUMMARY

1. Simultaneous recordings were taken of respiration, intra-gastric pressure and the electromyogram of the antero-lateral abdominal musculature in nine healthy young male subjects in the supine posture.

2. During quiet breathing the respiratory variation in intra-gastric pressure was slight; there was no detectable muscular activity.

3. The changes occurring during increasing pulmonary ventilation are described. A level of pulmonary ventilation sufficient for most forms of exercise was attained with relatively slight respiratory variation in intra-gastric pressure.

4. Maximum voluntary breathing was associated with marked changes in intra-gastric pressure which rose abruptly at the beginning of expiration and fell abruptly at the beginning of inspiration.

5. The effects of coughing, the vital capacity test and static expiratory efforts are described.

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