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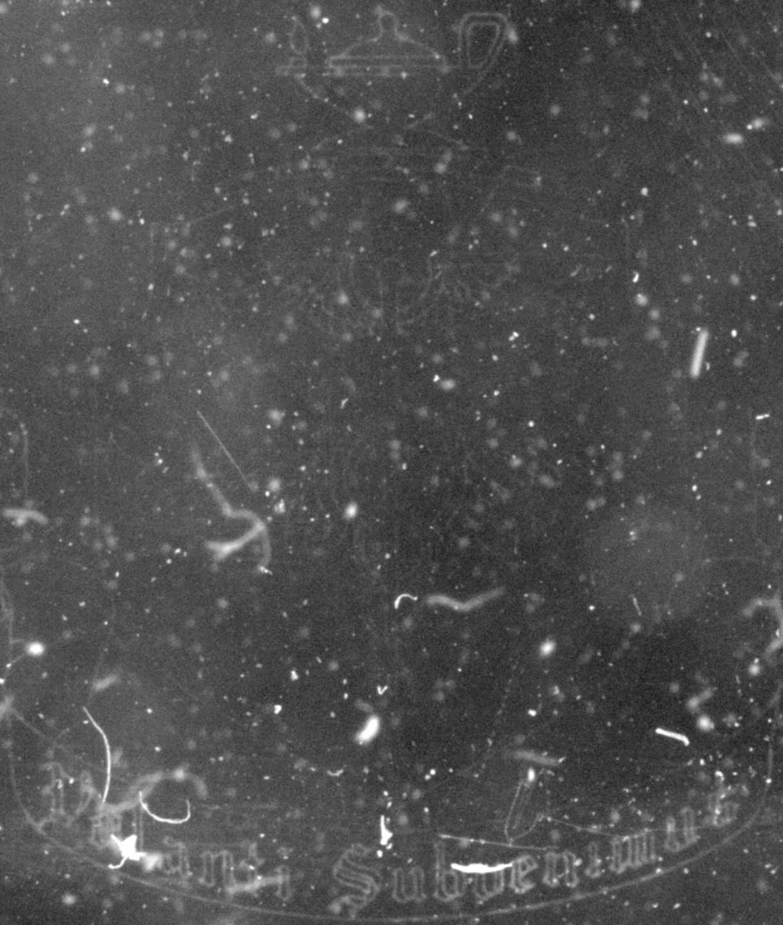

ABDOMINAL GAS VOLUME AT ALTITUDE AND AT GROUND LEVEL

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FOREWORD

This report was prepared in the Physiology Branch under task No. 775801. The research described was performed between 28 October 1966 and 6 June 1967. The paper was submitted for publication on 10 August 1967.

Critical comments on the observed net increase in water displacement by the lower body were given by Dr. H. G. Clamann. Dr. M. Bryan Danford advised on the statistical aspects of the work. K. S. K. Chinn had previously assisted in unpublished determinations of body volume increases resulting from gas-forming food. C. J. Theis made most of the direct observations in the altitude chamber.

This report has been reviewed and is approved.

GEORGE E. SCHAFER
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ABSTRACT

The effect of decreasing pressure on abdominal gas volume in eighteen young military men was studied under simulated flight conditions and using a displacement volumeter. Studies showed that decompression causes the abdomen to expand but that relatively slight increase in intra-abdominal pressure occurs. Young military men at ground level ordinarily average 0.111 liter (BTPS) of abdominal gas—a statistically significant amount. This amount, in turn, is significantly less than the mean 0.218 liter (BTPS) occurring in subjects when a water-filled naso-gastric catheter connected to a pressure transducer was used. Expansion of the 0.104 liter of dry gases, with concomitant wetting, resulted in 0.500 liter (BTPS) of abdominal gas at an ambient pressure of 230 torr (≡ 29,600 ft. pressure : altitude). At this point, 50% of the subjects would be expected to report symptoms of abdominal fullness. At yet lower pressures, subjects reported pain in 6 among 36 man-flights, and at this time the average abdominal gas volume was computed to be 1.09 liters (BTPS).

ABDOMINAL GAS VOLUME AT ALTITUDE AND AT GROUND LEVEL

I. INTRODUCTION

By means of frequent collections, it is commonly estimated (5) that human beings daily pass as much as several liters of abdominal gas. This gas may arise from air swallowing, from chemical and microbial breakdown of materials within the alimentary tract, and from diffusion and, perhaps, evolution of gases within the system. At any moment the volume of abdominal gas is much less than the daily production. At one time it was claimed that 1 liter of gas was contained in the digestive tract (5). The method was later criticized as leading to overestimates (4, 11). Finally, from recordings of intra-abdominal pressure-volume relationships in an air-filled body plethysmograph, a mean volume of 0.116 liter was calculated (4). This remains a currently accepted value for the average volume of abdominal gas, even though a naso-gastric catheter and balloon, present during the measurements, could have led to air swallowing.

A water displacement volumeter can be constructed and calibrated to within a standard deviation of 0.016 liter (1). A willing subject in repeated submersions deviates no more than 0.1 liter in total body volume. Immersion to various morphologic levels is a convenient method of denoting partial volumes of the body (3). This method was also used to estimate the bouyancy needed for flotation of soldiers (2). As will be seen, a water displacement volumeter can be used for observation of the expansion of lower body segments during decompressions to an ambient pressure as low as can reasonably be permitted and yet avoid hypoxia.

Suppose, while the subject is standing in the volumeter with the water level at the midsternum, that the ambient pressure is decreased. Does the lower body expand significantly? Do slight changes in posture affect the accuracy of observation, and what level of accuracy is achieved as judged by the swallowing of a measured volume of water? Within these constraints and limits, it is possible to calculate from ΔV and ΔP relationships the volume of abdominal gas (V_{1a}) that would have been present at the original pressure (P_1) in order to account for the volume of gas (V_{2a}) recorded at the various low pressures (P_2) achieved by a controlled rate of decompression. In almost one-half of the observations a pressure transducer connected to a naso-catheter leading into the stomach was used to record the relatively slight pressure contribution on the part of the abdominal cavity (P_{1a} and P_{2a}).

II. PROCEDURE

Subjects were 18 military men in good health, aged 18 to 28 years; the majority ate meals in a mess hall, and the various observations were made soon after noon when the men may or may not have eaten a light lunch. One set of observations started with the introduction of an open-ended naso-gastric catheter. The subject then entered a large altitude chamber and began breathing aviator's oxygen through a MBU-5/P mask set for 3 torr (≡ 3 mm. Hg) of positive pressure. About 55 minutes later—during which time nearly all of the nitrogen originally dissolved in body water and one-third of that in body fat would have been eliminated (9)—the subject climbed onto a step-plate which was then lowered into warm water inside the volumeter (1) until the water level reached a crayon mark on the midsternum. To avoid interference from gas bubbles, the volumeter and its contained water had just been partly de-gassed by a 30-minute exposure to 70,000-ft. pressure:altitude (35 torr). Next, the naso-gastric tube was filled with approximately 5 ml. of water and connected to a strain gage manometer (Statham P23) located outside the volumeter at the water level. Three readings of the water level in an attached standpipe were made to the nearest 0.5 mm. at the end of quiet expirations; at this time a record of the abdominal pressure (P_{1a}) was obtained (Visicorder model 906B). The ambient ground level pressure (P_1) was noted to the nearest 1 torr (Wallace-Tiernan absolute pressure gage). Decompression at the rate of 4,000 ft. per minute was then started with stops of several minutes at various low pressures (P_2) while water levels and abdominal pressures were recorded at the end of sets of three quiet expirations. The final stop was at $P_2 = 175$ torr ($\equiv$ 35,500 ft. pressure:altitude). The subjects were then returned to ground level and the several readings were repeated when the water level was at the midsternal mark. From start to finish a simulated flight lasted an average of 22 minutes.

To calculate dry abdominal gas at body temperature, observe from Boyle's law that

$$(P_2 + P_{2a} - P_w)\,V_{2a} = (P_1 + P_{1a} - P_w)\,V_{1a}$$

Transposing pressure terms from left to right and deducting V_{1a} from both sides leads to definition of

$$\Delta V_a = \left(\frac{P_1 + P_{1a} - P_w}{P_2 + P_{2a} - P_w} - 1\right) V_{1a} \ldots [\text{BTPD}]$$

from which V_{1a} can be calculated, provided that the volume change can be ascertained accurately and that account is taken, if possible, of slight postural changes and of loss of gas. ("Small" uncontrollable eructations were infrequent, and never in this situation did flatulence occur.)

In terms of the actual parameters for wet gas at body temperature reduced to prevailing ambient pressures close to 745 torr

$$V_{1a} = \frac{(P_2 + P_{2a} - P_w)^2}{(\Delta P + \Delta P_a)\,(P_2 + P_{2a})}\,\Delta V_a \ldots [\text{BTPS}]$$

and from this it also follows that

$$V_{2a} = V_{1a} + \Delta V_a .$$

A second set of observations without the catheter was made as a check on whether air was swallowed during introduction of the catheter. It was assumed that intra-abdominal pressure was 4 torr greater than the external ambient pressure. Oxygen prebreathing lasted 37 minutes and the "flight" lasted 15 minutes.

Additional control observations on the combined effect of postural and volume changes included the drinking of 500 ml. of water while the subject remained in the volumeter at "ground level." Among 11 men the expansion was observed on 8 separate days by noting in triplicate the net rise of the contents of the volumeter at the end of quiet expirations before and after the swallowing of the water. The individual expansions altogether amounted to a mean deviation from the expected of −0.058 liter with a standard deviation of 0.162 liter.

Examination of 75 additional sets of triplicate readings to the nearest 0.5 mm. showed from mean deviation and variance relationships, $\bar{d}/s_{\bar{d}} > 2$, that a net rise within the water displacement volumeter had to exceed 1.00 mm. in order to be significant by this definition. With a calibration factor of 0.253 liter per millimeter, this amounts to 0.25 liter in order to be assured of a significant expansion.

III. RESULTS

Figure 1 shows that it was difficult to judge the extent of individual expansion of the lower body after decompressions from 747 to 380 torr. At yet lower pressures, considerable expansion definitely occurred. It made some difference whether (filled circles) or not (circles) a naso-gastric tube was present. Compared with the volume prior to decompression the lower body, at the mark on the midsternum, was not significantly smaller upon return to the initial pressure (crosses); −0.024 liter with standard deviation of 0.138 liter. Thus, it was doubtful that there was any great loss of abdominal gas while subjects were at low pressure.

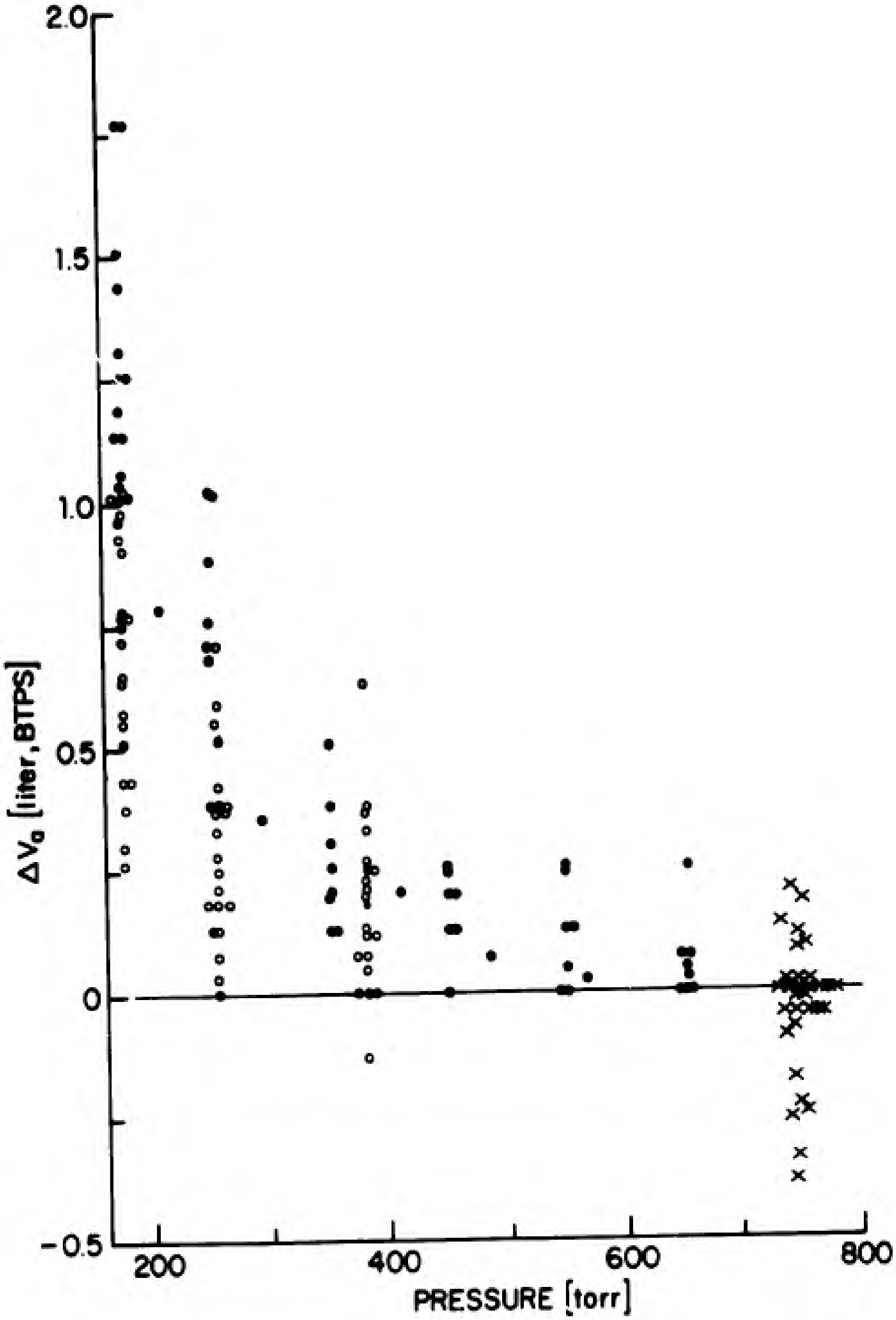

FIGURE 1

Expansion below midsternum upon slow decompression from P_1 *= 745 torr (≡ mm. Hg) to indicated values of* P_2*;* filled circles, *with water-filled open-ended naso-gastric catheter connected to pressure transducer;* circles, *without such a catheter;* crosses, *differences in lower body volume at "ground level" following the decompressions.*

Shown in figure 2 are measured changes in abdominal pressure at various ambient pressures starting at approximately 745 torr. On the average the decompressions down to 175 torr caused the abdominal pressure to increase to 7.2 torr with the indicated lesser increases at intervening ambient pressures.

In accordance with the final equation derived, individual volumes of abdominal gas were calculated from the observed expansions at 258 and 175 torr. These volumes (V_{1a}) were significantly greater for the 27 observations in the presence of a naso-gastric tube than for the 36 observations in its absence. In both types of observations there was no significant difference between the mean reduced volumes at either low pressure. Means together with standard deviations in milliliters, BTPS, were as follows when corrected to 745 torr:

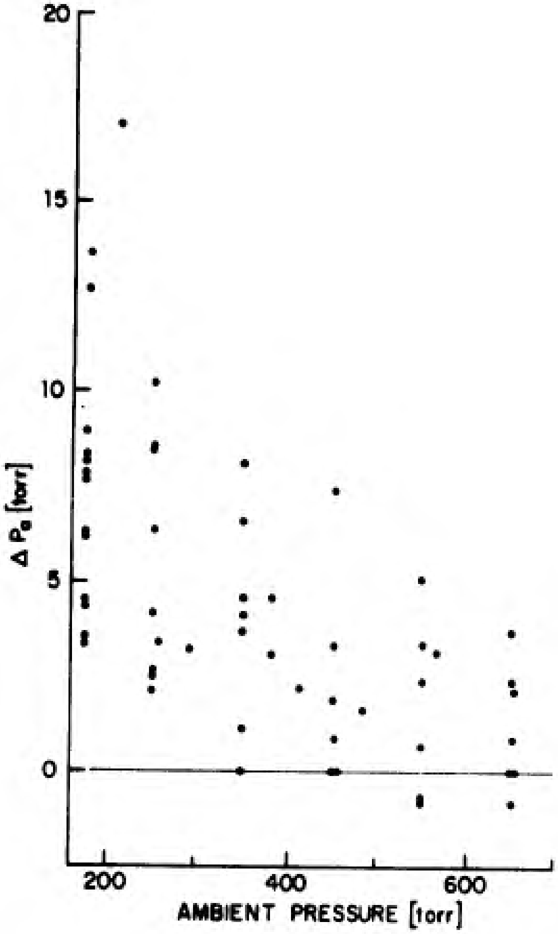

FIGURE 2

Increase in intra-abdominal pressure upon slow decompression at 4,000 ft. per minute.

	$P \cong 258$	$P \cong 175$	Both
With tube:	222 (98)	215 (63)	218 (78)
Without tube:	106 (69)	116 (40)	111 (56)

Altogether it seemed, as can be seen from a statistical frequency diagram (fig. 3), as though a naso-gastric tube caused the additional accumulation of 107 ml. of abdominal gas, perhaps because of excessive salivation and swallowing together with the slight positive pressure breathing. When decompressed and wetted, the dry content of the additional abdominal gas would therefore have accounted for the greater body expansions seen in figure 1 (circles vs. filled circles).

Among the total of 36 "flights" on the part of 18 men, the reported sensations ranged from negative to fullness and pain. Through pressures from 745 to 632 torr, only one man reported fullness and this only once. At yet lower pressures, more frequent reports were obtained until, in the pressure range from 226 to 175 torr in a total of 36 "flights," 30 men had reported either fullness or pain. Thus, in figure 4 (right-hand scale) the ratio 30:36 $\cong$ 0.83 was plotted (circle) at the average pressure of 200 torr for this step in the total pressure range. The curve, which closely agrees with the observed frequency of symptoms between 0.3 and 0.8, describes the abdominal gas volume (left-hand scale) at various low pressures in accordance with the equation, also shown in figure 4, using $V_{1a} = 0.157$ liter as the grand average. If, more realistically, $V_{1a} \cong 0.111$ liter, the curve would be displaced to the left indicating that when 50% of the men were affected, there would be 0.50 liter of abdominal gas at an ambient pressure of 230 torr $\cong$ 30,000 ft. pressure:altitude. Abdominal pain was described in 6 of the 30 reports, and occurred at an average volume of 1.09 liters (BTPS). This volume, as indicated by the asterisk symbol in the right hand curve of figure 4, would normally occur in the left hand curve at a pressure $\cong$ 141 torr $\equiv$ 40,000 ft. pressure:altitude. This then is the altitude at

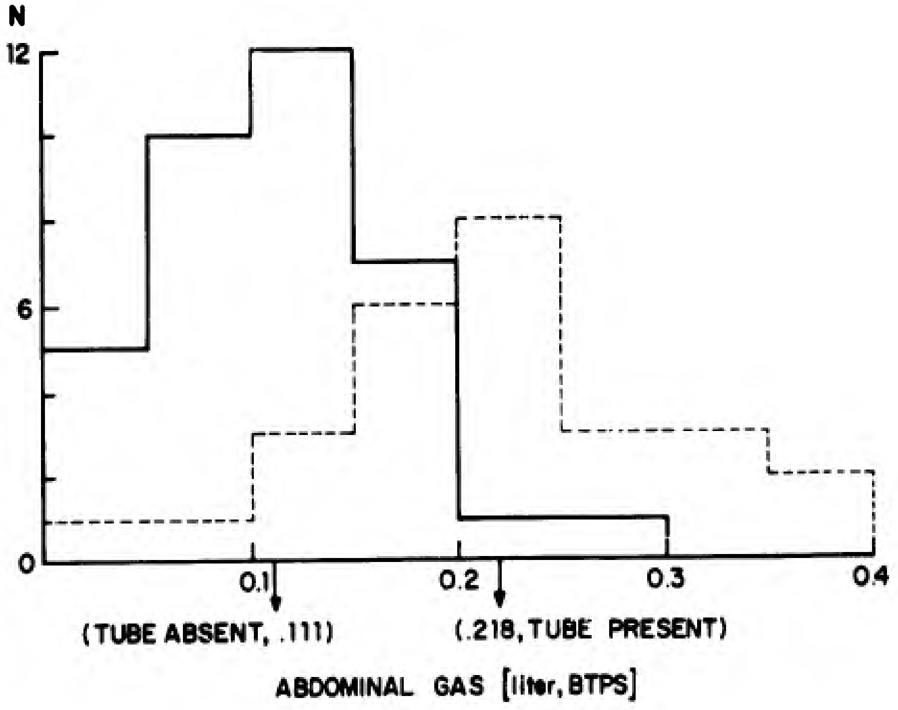

FIGURE 3

Frequency diagram of abdominal gas volumes at $P = 175$ and $P = 258$ torr (≡ mm. Hg) when reduced to "ground level" pressure of $P = 745$ torr; **dashed line,** *with naso-gastric catheter (27 observations);* **line,** *without such catheter (36 observations).*

which a sizable proportion of men would be expected to report pain if they started with 104 ml. of dry gas (≡ 111 ml. of wet gas) and retained it throughout the expansion and wetting involved in a decompression to this altitude.

IV. DISCUSSION

In the absence of critically accurate methods of observing the quantities of abdominal gas, many investigations have apparently confused the frequency and amount of passage of flatus with the quantity of gas residing within the gastrointestinal tract. From geometric surveys of roentgenologic studies, Keys and Brozek (8) concluded that 0.05 to 0.1 liter was about the upper limit in a normal subject who had just voided flatus. Hanson's striking roentgenographs taken at the pressure:altitude of 10,000 meters (7), certainly seem to apply to the 6 subjects previously mentioned who reported pain and had an average of 1.09 liters of abdominal gas. Bedell et al. (4) found, at ground level in Philadelphia, that introduction of approximately 1 liter of air into the colon would often evoke pain, and their roentgenographs appear to be similar to Hanson's. Instead of introducing gas through a syringe, Allen and Chinn, in unpublished, though pertinent, observations once noted the increase in body volume of a subject after ingestion of 0.6 kg. of commercially available canned baked beans. The subject in this study agreed to retain abdominal gas for as long as possible thereafter. At hourly intervals, the body weight and total body volume (1) were noted. It became evident that at least 1.4 liters of abdominal gas had accumulated during the ensuing 10 hours. Long prior to this time, abdominal fullness was noted. Eventually a vaguely painful sensation developed and persisted for several hours, but it was immediately

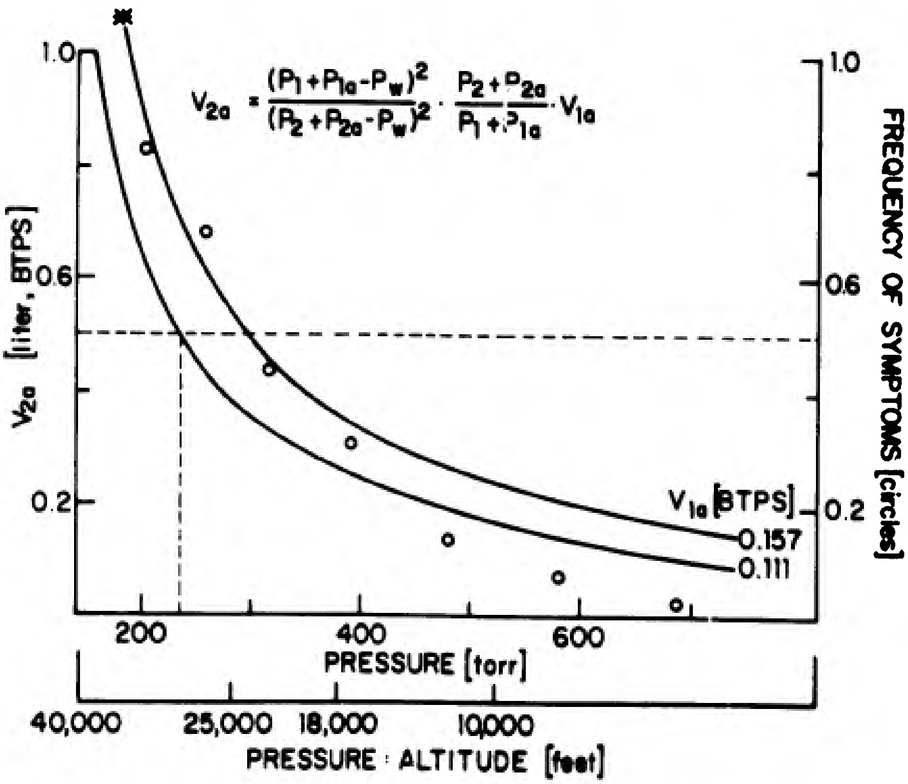

FIGURE 4

Prediction of abdominal gas volume at low pressures compared with frequency of symptoms reported in 36 "flights."

relieved at the 10th hour by two passages of gas amounting to an immediate total decrease in body volume of 0.8 liter. It is concluded that as little as 0.05 liter and as much as 1.4 liters of gas can occur within the gastrointestinal tract as a result of eating gas-forming foods. The upper limit rarely occurs except in emergencies and in otherwise normal persons voluntarily deciding to tolerate sensations of abdominal pain.

In the course of the present studies, careful consideration was given to the possibility that upon decompression, there are certain gases which could evolve from solution within the gastrointestinal tract. If this were so, then upon recompression and redissolving the volume of residual gas according to Henry's law would be approximately 0.05 liter instead of the 0.111 liter calculated thus far. Apparently there are several reasons why this does not happen. Even though a considerable decompression causes much expansion of the abdomen (fig. 1), there always appears to be a slight positive intra-abdominal pressure (fig. 2) tending to retain dissolved gases in solution. Further, if abdominal gases also evolved from solution, one would expect considerably more gas at $P = 175$ torr than at $P = 258$ torr from application of Boyle's law alone. Instead, the calculated volumes when corrected to $P = 745$ torr were not significantly different in a total of 36 paired observations at either of these low pressures.

The intricacies of abdominal gas phenomena involve not only volume but also composition. Figure 5 shows a schematic diagram of the gastrointestinal tract and its blood supply connecting with the lungs. Calloway (6) has

FIGURE 5

Model indicating both "closed" and "open" aspects of abdominal gas within the gastrointestinal tract.

shown that the lungs expire measurable quantities of hydrogen arising from within the gastrointestinal tract. Although the gastrointestinal tract evidently can act as a closed container, allowing gases to expand and contract, these gases change in composition in accordance with diffusion and perfusion.

Steggerda et al. (10) observed the partial composition of fairly large "gas pockets" introduced into the colon In general, their data show that the partial pressure of carbon dioxide remained at 64 torr, or slightly less, while the subjects were breathing oxygen and decompressing from 741 to 483 and 282 torr. At the same time the oxygen partial pressure fell from 92 to 44 and 23 torr, respectively. Allowing for maintenance of water vapor at a pressure of 47 torr, there remains a net difference of 537, 326, and 153 torr, respectively, of gas that was inert in the presence of simple chemical reagents. With these numerical values, it is possible to construct a fairly complete partial pressure diagram from which one can extrapolate linearly to the various partial pressures occurring at a total pressure of 175 torr. This is believed to be an accurate paraphrasing of available knowledge (10) on abdominal gas composition pertinent to a flyer's operational situation while decompressing and breathing oxygen. Future studies should use a small "gas pocket" at the start of decompression and include direct analyses of nitrogen, hydrogen, methane, and other gases, together with observation of the effect of oxygen breathing in the absence of decompression.

Application of available knowledge, nevertheless, reveals events of considerable interest that presumably affect the composition of the 104 ml. of dry abdominal gas during "flights" to 175 torr (≡ 36,000 ft. pressure:altitude). The postulated change in partial volumes shown in figure 6 indicate that 42.6 ml. of nitrogen and other gases would be replaced with the same volume of carbon dioxide. The principal dry gas volumes in milliliters occurring at body temperature and reduced to a pressure of 745 torr would be as follows:

P	O_2	CO_2	N_2, etc.
745	13.7	9.5	80.8
175	13.7	52.1	38.2

Oxygen breathing apparently removes nitrogen from abdominal gas and at the same time

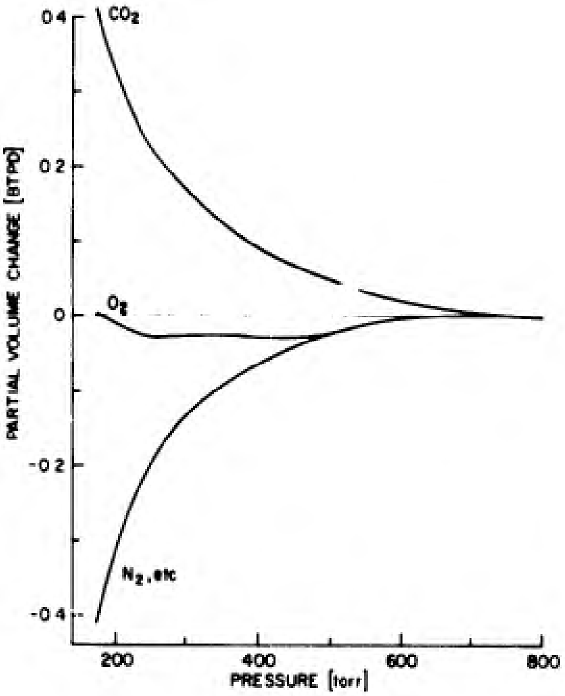

FIGURE 6

Change in partial volume of principal abdominal gases upon decompression with oxygen breathing (modified in accordance with data in reference 10).

eliminates dissolved nitrogen from body tissues. Its replacement with carbon dioxide would perhaps account for the slight nonsignificant loss in abdominal volume upon recompression to ground level (fig. 1, crosses). During that time, owing to greater diffusivity, the 52.1 ml. of carbon dioxide would leave the abdominal gas faster than the 38.2 ml. of nitrogen would increase as the subject returned to air breathing at less than 10,000 ft. pressure:altitude.

Abdominal gas volume pertains to the volume-weight relationships from which body fat is commonly calculated. Gross body composition ideally is derivable from simultaneous measurements of body volume (V), weight (M), and water (W). In practice, with normally hydrated subjects it is convenient to omit the measurement of body water (1); the general expression for body fat then becomes

$$F = C_1V - C_2M$$

where

$$C_1 \cong 4.8 \text{ kg./liter}$$

The technical error in determination of M is small relative to V. Thus,

$$\text{Var}(F) = C_1^2 \text{ Var}(V)$$

From the total body volume measured by displacement of water (V_e) one could deduct the residual lung volume (V_r) and the abdominal gas volume (V_a) in order to state the body tissue volume (V) as

$$V = V_e - V_r - V_a$$

Thus, the variance of V through propagation of errors is

$$\begin{aligned}\text{Var}(V) &= \text{Var}(V_e) + \text{Var}(V_r) + \text{Var}(V_a)\\ &= 0.0100 \quad + 0.0035 \quad + 0.0032\end{aligned}$$

The numerical value for V_e can be found in Allen (1); for V_r in Von Döbeln (11); and for V_a from figure 3. It then follows by substitution that the standard deviation for determination of fat from body volume and weight is $\sigma_F = 0.62$ kg. Nearly equal contributions to the total variance arise from determinations of residual lung, abdominal gas, and total body volumes.

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