Hemodynamic Effects of Continuous Positive and Negative Pressure Breathing in Normal Man

By Kaye H. Kilburn, M.D., and Herbert O. Sieker, M.D.

Knowledge of human circulatory responses to continuous pressure breathing, whether above or below ambient pressure, is largely confined to data on arterial blood pressure, peripheral circulation, renal function, and redistribution of blood volume. In anesthetized animals, respiration with maintenance of positive airway pressure lowers systemic blood pressure and decreases cardiac output. Conflicting results have been obtained regarding the effect on the cardiac output in man. The extent to which compensatory mechanisms in the conscious human subject might prevent the effects produced in animals is unknown.

Pressure chambers, immersion, inspiratory obstruction, or hyperventilation have been employed to produce relatively negative intrathoracic pressures. These measures appear to increase cardiac output by enhancing venous return, although this effect has not been established unequivocally. Continuous negative pressure breathing, which should increase intrathoracic suction and enhance filling of the great veins and right heart, might be expected to raise cardiac output.

To elucidate the effects of continuous positive and negative pressure breathing on the circulation, the response of the central blood volume and cardiac output to a sustained increase or decrease of airway pressure was studied in healthy young men.

Methods

Twenty-three normal male university students, aged 21 to 28, without a history or clinical evidence of pulmonary, cardiac, or renal disease, were experimental subjects. Thirteen patients hospitalized for dermatological or minor gastrointestinal complaints formed the remainder of the experimental group.

Experiments were done in a postabsorptive state, usually in the midafternoon. Base-line observations of cardiac output and blood volume immediately preceded the determination of these parameters during positive or negative pressure breathing. All measurements were made with the subject supine, loosely clothed, and at an environmental temperature of approximately 72 F.

Subjects breathed at a negative pressure through a face mask attached to a 40-liter reservoir, evacuated by a pump. The airway pressure was regulated by adjusting an air leak to produce negative inspiratory pressure of 20 to 22 cm. H2O in one group, and 12 to 14 cm. H2O in the other group of the series. Pressure was monitored by a water manometer attached to the face mask.

Continuous positive pressure was provided by connecting a compressed air tank, via a demand-feed regulator (Bendix model), to a valved airforce type face mask, with expiration to room air on exceeding the metered pressure. Positive pressure breathing of 5 per cent carbon dioxide in air was administered with the same apparatus. Airway pressure was maintained at 24 to 28 cm. H2O on expiration, with an inspiratory fall to 16 to 22 cm. H2O with quiet respiration. Respiratory patterns in most individuals were altered by negative pressure to lengthen the inspiratory phase, while positive pressure caused a rise in respiratory rate.

Indicator dilution curves for the calculation of cardiac output and central blood volume were recorded directly from the brachial artery blood which was pulled through a photoelectric cuvette (Colson densitometer) by a constant speed suction syringe. Evans blue dye was injected from a calibrated catheter placed in the superior vena cava in the central injection group, or from a needle in an antecubital vein in the peripheral injection se-
In the negative pressure breathing experiments, peripheral injections of Evans blue dye was utilized in 1 group of 8 subjects, while central injection was employed in another group of 7 subjects to avoid the possibility that extrathoracic venous collapse might interfere with the passage of dye into the intrathoracic veins. Central injection was used in all of the positive pressure breathing studies. Cardiac output and central blood volume were calculated by the method of Stewart and Hamilton. The area under the recorded venous collapse might interfere with the passage of dye into the intrathoracic veins. Central injection was employed in another group of 7 subjects to avoid the possibility that extrathoracic venous collapse might interfere with the passage of dye into the intrathoracic veins. Central injection was used in all of the positive pressure breathing studies. Cardiac output and central blood volume were calculated by the method of Stewart and Hamilton. The area under the recorded curve was integrated arithmetically after semilogarithmic plotting to obtain a theoretical disappearance time. While the quantitative accuracy of cardiac outputs recorded through a cuvette densitometer by indicator-dilution techniques may be questioned, the method seemed applicable to the measurement of acute changes in a short duration experiment. The reliability of the conventional Fick method, depending on accurate collection of expired air and mixed venous samples, appeared open to more question than the technic adopted.

Normal arterial, central venous, and airway pressures were recorded through pressure transducers on a direct-writing recorder, during the resting state and at intervals during pressure breathing. Plasma volume was estimated by the dilution of intravenously administered radioidine tagged human serum albumin. Samples from the brachial artery at regular intervals from 30 seconds to 20 minutes provided a dilution curve. After 30 minutes of pressure breathing, blank samples were obtained, and a second dose of tagged albumin was administered for estimation of plasma volume following pressure breathing. Calculation of the second plasma volume on the basis of the blank samples or readministration technic gave comparable results.

The alteration of pulmonary blood volume or relative blood density of the lungs was estimated in 1 group of 7 subjects given 50 mc. of I\(^{131}\) labeled human serum albumin for direct counts from the posterior right mid-chest. The honeycomb (QSS) collimator of a shielded gamma sensitive probe scintillation counter (Model DS 51P, Nuclear-Chicago Corp.) was placed against the chest wall below the scapula of the supine subject and centered 7 to 8 cm. from the mid-spine. The 2 x 2 inch sodium iodide crystal had a focal depth of 4.5 cm. with the described collimator and a cone-shaped field with a 5 cm. diameter. This area contributed 80 per cent of the total activity recorded. Counts were recorded automatically on a high voltage binary scaling unit (Model 183-B, Nuclear-Chicago Corp.). After background counts were obtained, I\(^{131}\) labeled albumin was injected intravenously, and 6 to 10 sets of 1- or 2-minute counts were made for control values. Counts recorded during Valsalva experiments and positive or negative breathing were expressed as percentage of change from the resting value.

A more direct assessment of the relative volume of intrathoracic structures was attempted by measuring the transverse diameter of the heart and the diameter of pulmonary venous segments in the frontal plane. Conventional planigrams were made without injection of contrast media at the level of 8 or 9 cm. anterior to the back in 3 subjects. Following a midinspiratory planigram at rest, each subject breathed for 5 minutes with continuous negative or positive pressure and repeat planograms were made at the same point of mid-inspiration.

Results

**Negative Pressure Breathing**

Negative pressure breathing (NPB), with an average inspiratory pressure of —20 to —22 cm. H\(_2\)O, and an expiratory pressure of —12 cm. H\(_2\)O decreased intrathoracic pressure, as reflected by negative airway pressures and a mean decrease of 10.5 mm. Hg in central venous pressure for the group. Table 1 summarizes the results obtained.

Cardiac index was increased, after 20 to 30 minutes of negative pressure breathing, from a mean resting level of 2.6 to 3.4 L/min./sq.m. in the central injection group. In the peripheral injection group, breathing at —12 to —14 cm. H\(_2\)O increased cardiac index from 2.8 to 4.0 L/min./sq.m. (table 1). Stroke volume increased from a mean value of 68 to 98 ml. in the latter group without significant changes in heart rate. In the group who breathed at —20 to —22 mm. Hg, cardiac output rose primarily because of an increased heart rate, and stroke volume showed no significant change. Systemic blood pressure showed exaggerated phasic variations, coincident with respiration suggesting giant Traube waves. Both diastolic and systolic pressures during negative pressure breathing were slightly above control values in most of the subjects. Continuous negative pressure breathing did not alter the partial pressure of arterial blood carbon dioxide, eliminating significant hyperventilation or hypoventilation as a factor in the circulatory changes.

Central blood volume, as calculated from
Hemodynamic Effects of Negative Pressure Breathing

Table 1

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<tr>
<th>Subject</th>
<th>Cardiac index L./min.</th>
<th>Stroke volume ml.</th>
<th>Heart rate beats/min.</th>
<th>Blood pressure mm. Hg</th>
<th>Central blood volume ml./sq.M.</th>
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*Two sets of readings indicate respiratory fluctuation in pressure.
†Negative pressure 20 to 22 cm. H2O.
‡Negative pressure 12 to 14 cm. H2O.

the dye curve, showed a small increase by a mean value of 65 ml./sq.M. External scintillation counts recorded from the lungs failed to show any significant or consistent change during negative pressure breathing. Counts recorded from over the heart showed a small but consistent increase in the counts per minute with a mean change of 17 per cent in 3 patients. Body section radiography demonstrated an increase in diameter of the heart and pulmonary veins in the right hemithorax.

Plasma volume did not change, averaging 1,596 ml./sq.M. body surface area at rest and 1,619 after 30 to 60 minutes of negative pressure breathing.

Positive Pressure Breathing

Breathing with positive pressure (PPB) increased the respiratory rate and produced an airway pressure of 26 to 28 cm. H2O on expiration, and 16 to 22 cm. H2O during inspiration. Central venous pressure rose by a mean value of 11 mm. Hg. Table 2 summarizes the results obtained.

Cardiac index measured after 20 to 30 minutes of breathing with positive pressure was decreased from a mean of 3.7 to 2.5 L./mi./sq.M. in 6 subjects who did not hyperventilate. Cardiac output of subjects, who more than doubled their minute ventilation, either showed no change or increased slightly. Table 2 presents the contrasting effects of positive pressure breathing with hyperventilation (HPBP) and without hyperventilation (PPB). Two subjects, who hyperventilated, complained of faintness and dizziness and showed tetany and carpopedal spasm consist-
POSITIVE AND NEGATIVE PRESSURE BREATHING

Table 2
Hemodynamic Effects of Positive Pressure Breathing

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<tr>
<th>Subject</th>
<th>Cardiac index L./min./sq.M.</th>
<th>Stroke volume ml.</th>
<th>Heart rate beats/min.</th>
<th>Blood pressure mm. Hg*</th>
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*Two sets of readings indicate respiratory fluctuation in pressure.
1HPPB = hyperventilation and positive pressure breathing.

ent with hypocapnea, but maintained their cardiac output, stroke volume, and central blood volume. Two subjects, who showed slight overbreathing and a fall in cardiac output and central blood volume on positive pressure, subsequently raised their ventilation to 30 L/min. for a 5-minute period. They showed a decrease in partial pressure of carbon dioxide in the arterial blood of about 50 per cent and a restoration of cardiac output and central blood volume toward normal. Another subject, who more than doubled his ventilation while breathing 5 per cent carbon dioxide in air at the same positive pressures, hyperventilation with room air or 5 per cent carbon dioxide in air appeared to be equally effective in providing circulatory compensation during positive pressure breathing.

Cardiac stroke volume fell by 21 to 62 per cent in individual experiments and paralleled the drop in cardiac output, but showed an increase when cardiac output rose. Heart rate increased in 9 of 12 patients, irrespective of the rate or volume of ventilation. The systemic blood pressure showed exaggerated phasic
variations with inspiration and expiration, and a slight rise of mean pressure. In 2 sub-
jects, warmed by room temperature of 85 to
90 °F., during positive pressure breathing, the
cardiac index decreased 1.7 L/min./sq.M. (mean value) and the mean arterial pressure
fell 30 mm. Hg (mean value). At room tem-
peratures of 72 °F., the same level of positive
pressure breathing decreased the cardiac index
only 1 L/min./sq.M. and did not alter sig-
nificantly mean arterial pressure. The oxy-
gen consumption was unchanged by pressure
breathing.

Central blood volume, calculated from dye
curves, fell as much as 50 per cent, with a
mean change of 217 ml./sq.M. in subjects
whose cardiac output dropped. In the group
who hyperventilated, an insignificant change
was noted in central blood volume. With the
external chest scintillation counter technic,
the counts dropped a mean of 16.1 per cent
during positive pressure breathing, and paralle-
led the 20 per cent drop produced in 3 sub-
jects by the Valsalva experiment. Body sec-
tion radiography demonstrated a decreased
cardiac diameter and a striking degree of nar-
rowing of the pulmonary veins in the right
hemithorax.

The plasma volume was not altered signif-
ically from a mean of 1,566 ml./sq.M. body
surface by positive pressure breathing for 30
to 50 minutes.

Discussion

Continuous breathing with decreased intra-
thoracic pressure without hypocapnia exag-
gerates the inspiratory phase of normal ven-
tilation, reduces vital capacity, 11, 12 produces
a water diuresis, 7, 8, 10 and causes vasodilation
in skeletal muscles of man and anesthetized
animals. 3, 5 Continuous voluntary overbreath-
ing in man produces similar effects if both
amplitude and rate of respiration are in-
creased. 5, 23 Norlin 24 showed an increase in car-
diac output and oxygen consumption, correlat-
ing well with the increase in minute ventila-
tion and fall in alveolar tension of carbon
dioxide in 5 normal men. However, with a
fixed respiratory rate of 6 per minute, Kety
and Schmidt 25 found voluntary doubling of
ventilation decreased cardiac output an aver-
age of 11 per cent in normal men. Whether
these responses differed because of hemody-
namic or neurophysiologic mechanisms has
not been established. A decrease in the volume
of the hand 37, 38 and increase in forearm blood
flow 5 accompany hyperventilation, but it is
not known whether this represents vasocon-
striction due to hypocapnia or to aspiration
of blood centrally by forceful inspiration. The
reduction in cerebral blood flow and increase
in cerebral oxygen consumption, 25 occurring
during voluntary hyperventilation reflexly
may stimulate intrathoracic circulatory ad-
justments and raise cardiac output.

Huggett 22 first demonstrated that negative
pressure breathing increased cardiac output
by an average value of 37 per cent, in studies
using urethanized cats breathing with inspira-
tory obstruction. A mean increase of 13 per
cent in the cardiac output of anesthetized
dogs breathing with a negative inspiratory
pressure of 16 cm. H2O was reported by
Holt. 15 Maloney 10 demonstrated that negative
pressure breathing in anesthetized dogs could
overcome the diminution in cardiac output
and blood pressure produced by positive pres-
sure breathing. Brecher, 39 utilizing the cath-
ter flowmeter in intact animals or a Pitot or
bristle flowmeter in operated anesthetized
dogs, has demonstrated increased flow in both
superior and inferior venae cavae during nor-
mal inspiration. Inspiratory flow is augmented
by Muller’s maneuver or rapid forced inspira-
tion. Holt 29 invoked the theory of partial
collapse of extrathoracic segments of large
veins, to explain the failure of negative pres-
sure to produce greater increments in vena
caval flow and right ventricular filling.

Methods of measuring flow in man must, of
necessity, be indirect, but have the advantage
of freedom from artifacts produced in experi-
mental animals by anesthesia, open chest, and
interruption of nerves. In man, decreased in-
trathoracic pressure, produced by negative
pressure breathing, reduced central venous
pressure and increased the flow gradient from

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the periphery. Widening of the cardiac silhouette and a slight increase in the width of central pulmonary veins were observed on planigrams made during negative pressure breathing and suggested an increase in cardiac volume. The total central blood volume, estimated by dye dilution, increased only slightly and lung field scintillation counting showed no significant change. Pulmonary blood flow measured as cardiac output was increased. It is of interest that Ernsting has reported a decrease of 50 per cent in pulmonary compliance, which he has attributed to pulmonary congestion during negative pressure breathing. The difference in stroke volume between the two groups (table 1) in the present series may be due to the production of extrathoracic large vein collapse during the forceful inspirations, produced by breathing against a pressure of 20 to 22 cm H₂O. This level represents about 4 times the negative pressure produced by quiet respirations. The effects of anxiety, connected with the introduction of the catheter into the vena cava, may be suggested as a possible mechanism for the difference between the groups, and, using pulse rate as an index of anxiety, this cannot be eliminated as a cause for this difference. However, the mean resting cardiac index was not different in the 2 groups and suggests that anxiety was not a major factor.

Negative pressure breathing does not increase the cardiac output in patients in congestive heart failure. (Kilburn, K. H.: unpublished observations). Left ventricular decompensation would be expected to nullify the effect of augmentation of right ventricular inflow and so produce no net change in measured cardiac output. Central venous hypovolemia increases the effect of inspiration on vena caval flow. It is also possible that vena caval engorgement might have the reverse effect.

Investigation of the circulatory response to positive pressure breathing, engendered by the use of pressure to increase effective alveolar oxygen tensions at high altitude, produced extensive literature on this subject, as reviewed by Werko. Data on the effects in both anesthetized animals and conscious man are in agreement as to the direction, if not to the degree of change. Comparison of results obtained by different investigators is complicated by varying methods of pressure administration, and the levels of both intermittent and continuous pressure adopted. The employment of flowmeter, dye dilution, and Fick techniques in intact or open-chest anesthetized animals and ballistocardiographic dye dilution, and Fick methods in conscious man appears to have increased the divergence of results. It might be predicted that the increase in pressure required for right ventricular filling (cardiac tamponade) and movement out of the central circulation would be proportional to the elevation of intrathoracic pressure, which is the product of airway pressure modified by the compliance of the lungs. This relationship should hold in intact organisms in which peripheral vasocstriction compensates, in part, for high intrathoracic pressure by returning toward normal the peripheral to central venous pressure gradient. The data of various investigators fail to bear this out. Effects observed on cardiac output vary from no change to a 76 per cent reduction produced by pressures varying from 8 to 24 mm Hg in anesthetized dogs.

In man, ballistocardiographic measurements showed no change or a small drop in cardiac output. Indicator-dilution and Fick techniques more consistently showed reductions of around 20 per cent in cardiac output, in both animals and man. However, the character of the ventilatory efforts, which might modify the response to a given level of continuous positive pressure, have seldom been regarded. More consistent responses to increments of pressure were obtained by Kaufman regarding pressures, and by Maloney and Braunwald with cardiac output determinations in anesthetized dogs using pressures from 17 to 26 cm H₂O and fixed respiratory pressures and rates. Blood pressure and heart rate fell, central venous pressure and intracranial pressure rose, and central blood volume and cardiac output fell. The consistency of these results in anesthetized animals when a Starling
type respiratory pump was used, and the variability in man suggested that the respiratory pattern adopted by the conscious subjects might be the factor which modifies the effect of positive airway pressure. Apparently, altering the effective duration of a given level of pressure produced the discrepancy in results observed in various groups of conscious subjects recorded in the literature and may be due to reflex or conscious respiratory responses to enhanced intrathoracic pressure.

In the present series of 6 individuals who did not increase their resting ventilation, cardiac output, stroke volume, and central blood volume fell in response to 30 minutes of positive pressure breathing at 26 cm. H_2O. Cardiac output fell by a mean of 39 per cent, and this failure to maintain circulation was exaggerated by warming the environment, suggesting that reflex peripheral vasoconstriction produced by positive pressure^10 could not overcome obligatory vasodilation for heat regulation. Effects resembling cardiac tamponade were produced and were reversible, either by reducing the airway pressure or by cooling the room.

In contrast to rest or negative pressure breathing, considerable narrowing of both the venous segments and heart shadow occurred during positive pressure breathing. The results of this more direct method, although difficult to quantitate, complement the changes in central blood volume obtained by less direct methods. The pulmonary veins and the cardiac chambers appear to comprise a central venous reservoir, responsive to pressure breathing.

The group in which the ventilation was increased either randomly—subjects 1 through 4—or by command—subjects 5 and 6 (table 2)—showed no significant decrease in cardiac index, stroke volume, or central blood volume. Central venous and arterial pressures showed accentuated oscillations without a mean change from resting values. The 2 subjects who responded to positive pressure breathing by lowering cardiac output, central blood volume, and stroke volume, when commanded to hyperventilate, reversed most of its effects. To ascribe these changes to induced hypocapnia necessitates postulation of a heretofore unrecognized effect of respiratory alkalosis. To explore this possibility, 2 subjects were hyperventilated on positive pressure and 5 per cent carbon dioxide in air. The fall in cardiac output and central volume, produced by positive pressure breathing, was overcome without developing hypocapnia. It seems reasonable to conclude that decreased intrathoracic pressure alone aids in aspiration of blood into the central venous reservoir.

The explanation of why some subjects assumed a pattern of overbreathing when exposed to positive pressure was not elucidated. This may have been the result of discomfort or anxiety. It may, however, depend upon carotid or aortic baroreceptor reflexes, activated by systemic hypotension, or upon reflexes from stretch receptors located in the pulmonary veins or lung tissue and mediated via the vagus nerve, since interruption of both vagi in animals has been shown to prevent spontaneous or reflex tachypnea.^45-47

The failure to demonstrate a change in plasma volume by the dilution of ^131-labeled human albumin, at a time when circulatory and renal effects were manifested, eliminates the possibility that decreased cardiac output and antidiuresis, observed in positive pressure breathing, are due to hypovolemia. However, 2 subjects, who initially in a warm environment showed bradycardia and marked hypotension, as well as dizziness, in response to positive pressure breathing, may well have experienced a considerable loss of blood volume into the splanchnic bed or extremities,^48 although by the present methods used this could not be demonstrated.

The divergence in results, measured by previous investigators, in response to both positive pressure breathing and hyperventilation, may be due, in part, to the combination of effects of these 2 potent and opposite circulatory stimuli. It appears logical, from the results of the present study, to suggest that hyperventilation effectively increases cardiac output and central blood volume in the pres-
ence of positive airway pressure, by improving aspiration of blood into the right side of the heart from depots. This is aided by vasoconstriction, which appears to be a compensatory reflex to positive pressure breathing. In the absence of vasoconstriction, or even in its presence, when the more potent vasodilatation for heart regulation prevents maintenance of intermediate blood depots, hyperventilation is less effective in augmenting cardiac output, and may actually fail to do so.

An explanation of therapeutic failure of positive pressure breathing in some patients with pulmonary edema may be found by carefully observing the pattern of respiratory response adopted. Vigorous overbreathing may actually enhance aspiration of blood into the chest and override the salutary extrathoracic pooling and decongestion of the central venous reservoir expected from administration of positive pressure.

It may be concluded from both the study of negative pressure breathing and hyperventilation, during positive pressure breathing, that decreased intrathoracic pressure does, in fact, aid considerably in maintaining or increasing the blood available to the heart in man.

Summary
Alterations in cardiac output, central blood volume, and arterial and central venous pressures were studied in 36 young men subjected to continuous negative or continuous positive pressure breathing. Negative pressure breathing increased cardiac output, stroke volume, and, to a lesser extent, central blood volume. Positive pressure, without overbreathing, decreased both cardiac output and central blood volume, but hyperventilation reversed these effects. On the basis of these observations, it is concluded that decreased intrathoracic pressure is important in maintaining or increasing the blood available to the heart in man, particularly during circulatory stress.

Summario in Interlingua
Le alterationes del rendimento cardico, del volumine central de sanguine, e del tensiones arterial e venose essera studiate in 36 juvene muscosis adulte durante le respiration continue sub pression negative o positive. Le respiration sub pression negative resultava in un augmento del rendimento cardico, del volumine per pulso, e minus marcatamente—del volumine del sanguine central. Pression positive, sin hyperrespiration, reduciva tanto le rendimento cardico como etiam le volumine del sanguine central, sed hyperventilation revertiva iste effectos. Super le base de iste observationes, le conclusion es formulate que un reduction del pression intrathoracica es importante in maintener o augmentar le sanguine que es disponibile al corde human, specialmente sub conditiones de stress circulatori.

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