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Positive Pressure Inspiration Differentially Affects Right and Left Ventricular Outputs in Postoperative Cardiac Surgery Patients

Paul C.M. Van den Berg, Cornelis A. Grimbergen, Joseph A.E. Spaan, and Michael R. Pinsky

**Purpose:** The purpose of this study was to determine the dynamic changes in right ventricular (RV) and left ventricular (LV) output during positive airway pressure inspiratory hold maneuvers so as to characterize the interaction of processes in creating steady-state cardiac output during positive pressure ventilation.

**Materials and Methods:** We examined the disparity of RV and LV outputs at 5 seconds (early) and 20 seconds (late) into a 25-second inspiratory hold maneuver in 14 subjects in the intensive care unit immediately following coronary artery bypass surgery. RV output was measured by the thermodilution technique, whereas LV output was measured by the arterial pulse contour method. RV and LV volumes were also measured by thermal and radionuclide ejection fraction techniques, respectively.

**Results:** As P<sub>aw</sub> was progressively increased from 0 to 20 cm H<sub>2</sub>O in sequential inspiratory hold maneuvers, both RV and LV outputs changed differently both at 5 seconds and 20 seconds into the inspiratory hold maneuvers. When expressed as change in cardiac output (L/min) for every cm H<sub>2</sub>O P<sub>aw</sub> increase relative to end-expiratory values, RV output increased at 5 seconds (0.05 ± 0.15 L/min) then decreased at 20 seconds (−0.08 ± 0.21, P < .05). LV output decreased slightly at 5 seconds (−0.14 ± 0.22) and did not change from this minimal depressed level at 20 seconds (P < .05). Changes in RV and LV output were paralleled by changes in RV and LV end-diastolic volumes, respectively.

**Conclusion:** Positive pressure inspiration induces time-dependent changes in central hemodynamics, which are dissimilar between RV and LV function. Initially, inspiration increases RV output but decreases LV output, such that intrathoracic blood volume increases. However, sustained inspiratory pressures induce proportionally similar decreases in both RV and LV outputs. Thus, the hemodynamic effects of positive pressure ventilation will depend on the degree of lung inflation, the inspiratory time, and when measurements are made within the ventilatory cycle. These data also suggest that positive pressure ventilation with up to 20 cm H<sub>2</sub>O P<sub>aw</sub> does not significantly impair ventricular performance in humans.

The application of positive pressure ventilation can have significant hemodynamic effects. Prior studies on the hemodynamic effects of intermittent positive pressure ventilation (IPPV) and positive end-expiratory pressure (PEEP) suggest that decreases in cardiac output that are usually seen are paralleled by decreases in intrathoracic blood volume owing to the associated decrease in systemic venous return. Furthermore, the decrease in cardiac output is proportional to the increase in mean airway pressure (P<sub>aw</sub>). These conclusions are often derived from hemodynamic comparisons made between steady-state control conditions off-PEEP and on-PEEP conditions. However, positive pressure inspiration may not affect the right and left ventricles equally. Nor may dynamic changes in intrathoracic blood volume be accurately modeled by analyses of steady-state hemodynamics. Recent animal studies suggest that continuous positive airway pressure (CPAP) and PEEP may not induce hemodynamically significant decreases in systemic venous return despite inducing increases in right atrial pressure (P<sub>aw</sub>). However, these observations have not been duplicated in humans. In part, duplication of such analyses in humans is hindered by difficulties in measuring instantaneous changes in right ventricular (RV) and left ventricular (LV) outputs and function during ventilation.

When P<sub>aw</sub> and lung volume are increased, some determinants of RV and LV performance may be altered in the same direction, whereas others may be altered in opposite directions. For example, both ventricles are subjected to the same extrinsic compression by the expanding lungs, possibly increasing ventricular interdependence. However, positive pressure inspiration may increase pulmonary vascular resistance, but the associated increase in intrathoracic pressure will decrease LV afterload augmenting LV ejection. Thus, increases

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in lung volume and intrathoracic pressure may initiate intravascular volume shifts, which result in a transient dissimilarity between RV and LV output.

Accordingly, we examined the transient disparity between RV and LV outputs after observing stepwise increases in Paw induced by airway inflation. Taking into account the time constants of the pulmonary and systemic vascular beds, we chose to examine differential RV and LV volumes and outputs at 5 and 20 seconds into an inspiratory hold maneuvers. This analysis allowed us to examine both early and late cardiovascular changes during inspiratory hold maneuvers.

MATERIALS AND METHODS

Fourteen postoperative cardiac surgery patients were selected for the study. The study was approved by the ethical committee for human experimentation of the hospital, and all patients gave informed consent before surgery. No complications occurred as a result of the study. All patients underwent uncomplicated coronary artery bypass grafting, were functionally and clinically free of congestive heart failure, and had a normal preoperative contraction pattern on left ventriculography.

Patients were excluded from the study if they had an LV end-diastolic pressure >15 mm Hg, LV ejection fraction <30%, atrioventricular conduction defects, arrhythmias, unstable angina pectoris, profoundly impaired myocardial pump function, or a preoperative diagnosis of myocardial infarction. All subjects had no more than mild obstructive pulmonary disease (forced expiratory volume 1 second [FEV₁] >75% of expired vital capacity). None of the subjects received β-adrenergic receptor blocking agents at the time of the study. The mean age of the subjects was 59 ± 9 years, and their mean weight was 78 ± 11 kg.

A randomly selected subgroup of six subjects was checked by trnasophageal echocardiography at zero and 20 cm H2O of Paw to evaluate whether an increase in Paw to 20 cm H2O resulted in a pressure-dependent tricuspid insufficiency. In none of these subjects could a Paw-dependent tricuspid insufficiency be detected. As a standard measure in all 14 subjects, the P, wave was also evaluated to detect patterns consistent with free of congestive heart failure, and had a normal preoperative contraction pattern on left ventriculography.

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The patients were instrumented with systemic arterial and pulmonary arterial catheters before the start of the surgical procedure to collect blood samples and measure pressures. A temperature of inspired air at 34°C was maintained. At the same time, this cold-induced reflex of the airways, care was taken to keep the temperature of inspired air at 34°C. At the same time, this prevented a drift of the baseline temperature of the pulmonary artery thermistor. RV ejection fraction (EFrV) was measured using a fast-response thermistor pulmonary arterial catheter, which has been validated against radionuclide techniques. Vascular and airway pressure measurements were made using high-fidelity transducers (HP Quartz transducers, Palo Alto, CA) and recorded on line as well as displayed on a video monitor (HP monitor 78347A, Palo Alto, CA) with a zero accuracy of ±1 mm Hg and a full-scale accuracy of ±3% after calibration. Pulmonary artery occlusion pressure (Paw) measured at end-expiration was used as an estimate of LV end-diastolic pressure as validated by others. When Paw was measured, it was done during inflow hold maneuvers in which cardiac output measures were not simultaneously measured. Systemic blood pressure was measured from a radial artery catheter. The intra-abdominal pressure (Pab) was measured via a transurethral bladder catheter according to a technique described by Kashtan et al and validated in both animals and humans.

Arterial Pulse Contour Method

A pulse contour method was used for the determination of instantaneous LV output (CO). The basic principle of this method is the analysis of the arterial pulse pressure profile. This method of determining cardiac output assumes a constant relationship between arterial pressure, aortic blood flow, and LV stroke volume. The pulse contour method has been compared with other cardiac output measuring methods, both in animals and humans. The correlation coefficient between the thermodilution and the pulse contour method is reported as ~0.90. We used the specific method of Wesseling et al. The advantage of this pulse contour method, compared with other methods, is that it adjusts for changes in mean arterial pressure, heart rate, and age-dependent characteristics of the aorta compliance. Using this method, the systolic area of the arterial pressure waveform is integrated and multiplied by the characteristic impedance of the aorta. Because the characteristic impedance of the aorta of each subject was not known, it was cross-referenced and calibrated by thermodilution cardiac output method during periods of prolonged apneic steady states (15 seconds). During such a steady state, this cardiac output value represents both RV and LV output, whereas during non-steady state, the thermodilution method only represents RV cardiac output (COV). The computation constant of the pulse contour method was then adjusted so that the thermodilution method and pulse contour method gave the same cardiac output results during apneic baseline measurements.

Nuclear Stethoscope Method

Relative changes of LV end-diastolic volume were measured using a nuclear probe (Nuclear Stethoscope, Bois Inc., Cleveland, OH). The nuclear probe is a nonimaging scintillation probe with a maximum count rate capacity of 140,000 counts/sec. Recordings of counts over the precordium were made of a 99m-technetium compound in the vascular pool. The high count rate of this marker allows the continuous beat-to-beat analysis of LV volume changes. Positioning of the nonimaging probe over the precordium requires orientation of the detector based on stroke counts (end-diastolic minus end-systolic) and average counts (end-diastolic plus end-systolic divided by two) as recorded by the probe. The LV region of interest was chosen as the position with the maximum ratio of stroke counts to average counts. The background area of interest is chosen as a position immediately inferolateral to the LV region of interest, where
stroke counts are minimal and average counts begin to decrease as previously described. This technique was used to estimate LV ejection fraction, which, when interfaced with CO-derived stroke volume data during apneic steady-state conditions, allowed for calculation of baseline LV end-diastolic volume as the ratio of LV ejection fraction to stroke volume. Similarly, the ratio of this dynamically changing LV ejection fraction to matched aortic pulse contour-derived stroke volume estimates allowed calculation of beat-to-beat changes in LV end-diastolic volume during inspiratory hold maneuvers.

**Protocol**

Patients were anesthetized with high-dose fentanyl. This anesthetic technique was used because of its stabilizing effects on the cardiovascular system during both the intraoperative and postoperative intervals. After the coronary bypass operation, all patients were transported to the intensive care unit, and after a stabilization period of at least 2 hours and at maximum 5 hours, a baseline hemodynamic analysis was performed. At that moment all hemodynamic variables (PVR, PAP, Pao2, CO2, EF, heart rate, and systemic blood pressure) had to be within 10% of the therapeutic goals determined by the operating team, otherwise the patient was not included in the study. All 14 subjects met these criteria. The experiments were started when the central body temperature was at least 37°C. During the experiments, all subjects were still under the sedative effects of fentanyl given during the operation.

The protocol consisted of repeated inspiratory hold maneuvers of 25 seconds duration. These inspiratory hold maneuvers were separated by 1-minute intervals to regain the same steady-state situation as before the first inspiratory hold. Resumption of a stable baseline was documented by restoration of all measured hemodynamic variables to within 10% of their initial baseline values. Then, the next maneuver was performed, with an inflation volume 250 mL greater than during the previous maneuver. In this way, a series of maneuvers resulted in a stepwise increase in both PVR and lung volume. During the first two duplicate inspiratory hold maneuvers, no gas was inflated in the lungs and the resultant PVR equaled ambient pressure. The hemodynamic measurements performed during these maneuvers were used to derive the baseline values of all variables against which changes induced by increased PVR were compared. Lung inflation was performed with the same FIO2 used to ventilate the subject. Accuracy of the PAP data during inspiration as not reflecting West zone 1 conditions was validated by the associated increase in PVR being less than the increase in PVR.

Each individual inflation challenge was divided into four phases as described in Fig 1. Phase I started at end-expiration and represents the pre-inflation period. In this period, the electronic sampling of data was started. Data sampled during this period were used to evaluate the hemodynamic status of the subject, and to evaluate whether hemodynamic deterioration outside the 10% range, as described in the protocol, had taken place. During phase II, an extra volume of gas was inflated in the lungs and created a peak pressure in the trachea. After this peak pressure, phase III started at the moment a plateau in PVR had been reached. The height of the plateau PVR was determined by the inflated volume, the functional residual capacity, and the compliance of the lungs and chest wall. All comparisons of hemodynamic and PVR data were made between baseline values during phase I and 5- or 20-second measured values during phase III. The maximal plateau PVR we strove for was 70 cm H2O. Phase IV describes the period in which PVR was allowed to return to its pre-inspiratory pressure by passive exhalation of the extra volume from the lungs.

The effect of an increase in PVR was evaluated after the pressure peak caused by the inflation with gas was passed and when the PVR had reached a plateau. In practice, all data used for further analysis were derived either 5 to 6 or 20 seconds after lung inflation was started. The trachal pressure was measured at the entrance of the endotracheal tube and was used to represent PVR. Two different thermomlution curves were recorded in phase III, one initiated at 5 to 6 seconds and another initiated at 20 seconds after PVR had hit a plateau. Each thermal injection was done during a separate inspiratory hold maneuver. All thermal decay profiles were inspected for an exponential thermal decay and return to its baseline value. If this was not the case, the measurements were discarded and the procedure repeated.

A time of 1 minute between consecutive inspiratory hold maneuvers was chosen because the time constant of volume shifts between the thoracic, abdominal, and peripheral compartments of the circulation is well within the order of 1 minute.
required by monitoring $P_{ta}$ (RV filling pressure) and $P_{pw}$. In this way, subjects were kept in a hemodynamic steady state throughout the protocol. Data from three of the subjects were discarded because of inaccurate pressure measurements. $S_{ao2}$ was continuously measured with a pulse oximeter (Nellcor) and end-tidal CO$_2$ levels were checked with a capnograph (Hewlett-Packard, Palo Alto, CA). During all experiments $S_{ao2}$ did not change and the end-expiratory CO$_2$ was stable within ±2%.

**Data Analysis**

All data were digitalized with a sample frequency of 100 Hz, the band width of the used signals being less than 50 Hz. The signals were converted with a 12 bits resolution and were stored on hard disk for later evaluation. Sampling of data started just before the beginning of an inspiratory hold and was stopped 4 seconds after termination of phase III of the maneuver.

The analysis of the data was concentrated on the changes in the hemodynamic variables induced by the increase in $P_{pw}$. Linear regression analysis was performed, using the method of least squares. The effect of changes in $P_{pw}$ on the measured hemodynamic variables (CO, CO$_2$, Ppa, PCWP) was made over the entire range of $P_{pw}$ changes and found to be linear. However, for illustration purposes, changes between 0 and 20 cm H$_2$O are described in the Figs 1 through 5. Analyses of the $P_{pw}$ effects on the measured hemodynamic variables were performed with repeated measurement analysis of variance using a post hoc test.
Fig 4. Relative changes of RVEDV after 5 seconds of increased \( P_{aw} \) per cm H\(_2\)O \( P_{aw} \) in 14 patients (A) and the same for LVEDV (B).

Student-Newman-Keuls test (RMDP-V statistical package, Berkeley, CA). Statistical significance reports differences corresponding to a \( P < 0.05 \) unless otherwise stated. Data are presented as mean ± SD.

RESULTS

The baseline hemodynamic data of the 14 subjects before starting the protocol are given in Table 1. An example of the relation between the inflated lung volume and \( P_{aw} \) is given in Fig 2. The increase in \( P_{aw} \) is transmitted to intravascular structures within the thorax and abdominal cavity, as illustrated during one inspiratory hold maneuver. Per patient, a mean of 7 ± 2 duplicate inflations of the lungs were performed before \( P_{aw} \) increased to approximately 20 cm H\(_2\)O. The \( P_{aw} \) range during the experiments ranged from 0 to 19.01 ± 2.7 cm H\(_2\)O.

Lung inflation induced by increases in \( P_{aw} \) increased the intrathoracic vascular pressures and differentially altered the RV and LV outputs in a time-dependent fashion. From a baseline CO\(_{v} \) of 5.72 ± 1.5 L/min, right-sided cardiac output, as measured by CO\(_{v} \) 5 seconds after the initiation of the plateau phase, increased 0.05 ± 0.15 L/min/cm H\(_2\)O. This slight increase in CO\(_{v} \) was significantly different from the slight decrease in CO\(_{v} \) simultaneously measured by the arterial pulse contour method. The change in CO\(_{v} \) was -0.14 ± 0.22
Table 1. Baseline Hemodynamic Data Before Lung Inflation

<table>
<thead>
<tr>
<th>Subject</th>
<th>MAP (mm Hg)</th>
<th>Ppa (mm Hg)</th>
<th>Pao (mm Hg)</th>
<th>CO (L/min)</th>
<th>EFv (%)</th>
<th>CI (L/min/m²)</th>
<th>SVI</th>
<th>EDVI</th>
<th>PCWP</th>
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Mean ± SD 75 ± 15 21 ± 5 9 ± 4 9 ± 6 5.74 ± 1.52 0.41 ± 0.09 2.93 ± 0.70 36 ± 10 88 ± 21 14 ± 2

Hemodynamic profile of 14 patients, whose data were used for analysis.

Abbreviations: MAP, mean systemic blood pressure; Ppa, mean pulmonary artery pressure; Pao, right atrial pressure; Pao, abdominal pressure; CO, right ventricular cardiac output; EFv, right ventricular ejection fraction; CI, cardiac index; SVI, stroke volume index; EDVI, end-diastolic volume index; PCWP, pulmonary capillary wedge pressure.

DISCUSSION

Our study demonstrates that positive-pressure inspiration induces time dependent differential effects on RV and LV output. These data demonstrate that RV filling, CO, and intrathoracic blood volume increase during positive-pressure inspiratory effort of up to a Pao of 20 cm H2O. Although CO was less than apneic baseline values at both 5 and 20 seconds into an inspiratory hold maneuver, these decreases were most pronounced at 5 seconds returning toward apneic values at 20 seconds. These dynamic changes suggest a complex process by which mean cardiac output is determined by ventilatory phase-dependent changes in both RV and LV function. Although our study could not separate out the selective effects of increases in Pao from increases in lung volume, these data demonstrate that mean cardiac output is not impaired by up to 20 cm H2O Pao increases to levels which would be clinically relevant (Table 2). Fessler et al. demonstrated in dogs that the application of up to 15 cm H2O PEEP did not alter the gradient for venous return. In support of these findings, they also observed a constant cardiac output. Their data agree with the flow data in our study in postoperative cardiac surgery patients.

Many prior studies in animalsm31,41,45 and humans11,36 have demonstrated that positive pressure inspiration decreases cardiac output. Braunwald et al. demonstrated that PEEP decreased cardiac out-
Table 2. Mean Hemodynamic Data During Apneic CPAP

<table>
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<tr>
<th>P&lt;sub&gt;aw&lt;/sub&gt; range</th>
<th>P&lt;sub&gt;aw&lt;/sub&gt; (cm H&lt;sub&gt;2&lt;/sub&gt;O)</th>
<th>P&lt;sub&gt;ao&lt;/sub&gt; (mm Hg)</th>
<th>P&lt;sub&gt;ao&lt;/sub&gt; (mm Hg)</th>
<th>P&lt;sub&gt;ao&lt;/sub&gt; (mm Hg)</th>
<th>P&lt;sub&gt;ao&lt;/sub&gt; (mm Hg)</th>
<th>CO&lt;sub&gt;2&lt;/sub&gt; (L/min)</th>
<th>RV&lt;sub&gt;cl&lt;/sub&gt;</th>
<th>CI (L/min/m&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>P&lt;sub&gt;ao&lt;/sub&gt; (mm Hg)</th>
<th>HR (beats/min)</th>
</tr>
</thead>
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<td>0-3</td>
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<td>21 ± 3.35</td>
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</tbody>
</table>

Note: Pooled mean data for all subjects grouped by date achieving the desired P<sub>aw</sub> threshold for each patient. Data are presented as mean ± SD. N = 14.
DIFFERENTIAL VENTRICULAR OUTPUT

pressure inspiration is also a matter of controversy. A decrease in LV volume during sustained increases in \( P_{aw} \) has been described in both animal and human studies. The decrease in LV end-diastolic volume was used to explain the decrease in cardiac output seen in these studies. However, increases in intrathoracic pressure induced by positive pressure ventilation will also decrease LV afterload, and this mechanism has been invoked to explain the observed increases in cardiac output in patients with heart failure following the application of PEEP. Additionally, an unchanged cardiac output during a Valsalva maneuver has also been reported and ascribed to squeezing of an overloaded pulmonary circulation. Our data support the hypothesis that if LV afterload was affected by these positive pressure inspiratory hold maneuvers, the effect was small. More likely, the decrease in CO reflects decreasing LV end-diastolic volume owing to ventricular interdependence, since RV end-diastolic volume also increased.

**Limitations of the Study**

Although CO, and CO, are measured with different techniques, a high correlation between the two methods has been established. Moreover, if the compliance of the vascular tree changed during the inspiratory hold maneuvers, it would most likely decrease when \( P_{aw} \) increased. This would result in overestimating CO, by the pulse contour method. We saw a decrease in CO, thus, the actual decrease in CO may have been even greater than observed. However, Versprille et al demonstrated that during changes in intrathoracic pressure, the aortic pulse contour method accurately reflects CO, when the mean arterial pressure does not change, as was the case in our studies. Clearly, CO, and CO, although starting at similar points before inspiration, change directionally in opposite directions with inspiration, demonstrate different time-dependent (5 and 20 seconds) phase changes, and demonstrate that markedly different forces interact to define the outputs of the two ventricles. Also, the study of either RV or LV function alone will not accurately describe the dynamic forces determining the equilibrium seen during ventilation.

A discrepancy between radial or brachial artery compared with aortic pressure has been observed in the postoperative period of cardiac surgery subjects. However, this post-bypass difference in central and peripheral systemic blood pressure is transient and resolves with the administration of fluid. Gravlee et al found no difference in radial, brachial, or aortic pressures 20 minutes after cardiopulmonary bypass. Finally, autonomic tone could have changes during the course of these maneuvers, minimizing any hemodynamic deterioration associated with increasing \( P_{aw} \). However, all subjects were under significant narcotic anesthesia during the time of study. Furthermore, both heart rate and calculated peripheral vascular resistance were constant. Accordingly, this human preparation reflects a model with almost no sympathetic responsiveness. In support of the argument that our subjects were markedly suppressed in their endogenous sympathetic responsiveness, six of the subjects had a baseline MAP of 60 mm Hg or less. However, in none of them was there evidence of tissue hypoperfusion, such as lactic acidosis oliguria, ECG changes of ischemia, or subsequent organ dysfunction.

**SUMMARY**

Our study demonstrates a differential effect of CPAP on RV and LV output, which is phase and time dependent. These changes in outflows are not predicted from assumptions based on selective changes in only \( P_{aw} \), pulmonary vascular resistance, or LV afterload unless one assumes that CPAP differentially alters both RV ad LV preload and afterload by affecting these variables, as well as maintains the pressure gradient for venous return.

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