Right Ventricular Function During Weaning From Respirator After Coronary Artery Bypass Grafting*  
Comparison of Two Different Weaning Techniques

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The purpose of this investigation was to determine right ventricular function during weaning from controlled ventilation comparing a biphasic positive airway pressure ventilatory support system (BiPAP [Respironics]) with pressure support ventilation (PSV). In 22 patients following coronary artery bypass grafting, both weaning techniques were used in randomized chronological order for 60 min each. Right ventricular end-systolic (RVESV) and end-diastolic volume (RVEDV) and ejection fraction (RVEF) were evaluated using the fast-response Swan-Ganz catheter. In comparison to PSV, the BiPAP system resulted in a significantly higher mean pulmonary artery pressure (20.6 ± 5.0 vs 19.3 ± 4.2 mm Hg, p=0.0158), pulmonary vascular resistance index (206 ± 55 vs 181 ± 61 dyn·s·cm⁻⁵·m⁻², p=0.0355), RVESV (92.2 ± 30.3 vs 77.2 ± 30.4 ml, p=0.0017), and RVEDV (176.4 ± 48.5 vs 161.8 ± 43.3 ml, p=0.0061), while the RVEF was significantly lower (46.0 ± 11.9 vs 51.8 ± 12.4 percent, p=0.0012). No differences in left ventricular function or arterial blood gas analyses were measured during both study periods. In summary, the RV afterload was higher with the BiPAP system compared with PSV which suggested that this was due to differences in the respiratory support between both weaning modes. Because of the Frank-Starling mechanism, this higher afterload did cause a small but significant increase in RV volumes and a significant decrease in RV ejection fraction with the BiPAP system. (Chest 1994; 105:1352-56)

Changes in intrathoracic pressure caused by intermittent positive airway pressure as well as positive end-expiratory pressure (PEEP) may influence left and in particular right ventricular (RV) function. Differences not only in the level of PEEP²⁻⁴ but also in the tidal volume,⁵ the inspiration:expiration ratio,⁶ and the mode of ventilation⁷⁻⁹ have been shown to result in differences in cardiocirculatory function due to changes in preload and afterload. Since an impaired RV is more dependent on optimal preload and afterload than a healthy ventricle due to a reduced ability to compensate changes in loading conditions,¹⁰⁻¹¹ the RV response seems also to depend on the baseline RV function.²¹¹,¹² Especially after cardiac surgery, RV function may be impaired¹³⁻¹⁵ requiring a precise monitoring of RV hemodynamics.¹²,¹⁵ Thus, the mode of ventilation and weaning may cause an important additional influence on RV function in these patients.

Pressure support ventilation (PSV) up to a pressure support level of +30 cm H₂O has been reported to be as safe and successful as continuous positive pressure ventilation with PEEP in patients after cardiac surgery.¹⁶,¹⁷ RV response, though, has not yet been assessed in these studies. There is no information available on RV function during a ventilatory weaning technique (biphasic positive airway pressure ventilatory support system [BiPAP-Respironics]) first described by Baum et al.¹⁸ Airway pressure release ventilation system, (APRV), a similar technique to the BiPAP system, is supposed to contribute to a greater hemodynamic stability than continuous positive pressure ventilation.¹⁹ Valentine et al.²⁰ described a higher PVR during APRV in comparison to PSV and no differences in other hemodynamic variables. Since RV volumes or RV ejection fraction (RVEF) were not evaluated in this study, further investigations are necessary to delineate potential hemodynamic differences in critically ill patients.²⁰

Therefore, the aim of this study was to assess RV end-systolic volume (RVESV), RV end-diastolic volume (RVEDV), and RVEF during postoperative weaning from controlled ventilation using PSV and the BiPAP system in patients after coronary artery bypass grafting. This study was designed to evaluate the influence of the respiratory support on RV function during weaning from ventilator support.
bypass grafting.

METHODS

Patient Selection

Following approval by the Human Investigations Committee of Ulm University and after obtaining written informed consent, 22 patients scheduled for elective coronary artery bypass grafting were investigated. There were 20 men and 2 women with a mean age of 65 years (range, 51 to 72 years). Coronary artery abnormalities included stenosis of the right coronary artery in 18 patients documented in the preoperative catheterization protocol. Patients with depressed ventricular function (left ventricular ejection fraction <40 percent, pulmonary capillary wedge pressure [PCWP] >18 mm Hg), pulmonary artery hypertension (mean pulmonary artery pressure [MPAP] >20 mm Hg), chronic obstructive lung disease, tricuspid valve incompetence, and patients with atrial fibrillation or other arrhythmias were excluded from the study.

Protocol

Coronary artery bypass surgery, anesthesia (fentanyl, fentanyl, pancuronium bromide in weight-dependent dosages) and postoperative management were performed as our standard procedures in all patients. Cardiopulmonary bypass was instituted with membrane oxygenators and a nonpulsatile flow of 2.4 L/min/m².² Brechtshneider cardioplegic solution was used for myocardial preservation; in addition, myocardial surface was cooled with ice-saline solution. During aortic clamping (ischemia), moderate hypothermia (32°C) was used. After successful operation controlled ventilation (IPPV, PEEP +5 cm H₂O) was continued in the ICU until hemodynamic stabilization and final rewarming. With patients awake and able to breathe spontaneously, weaning was started with PSV at +15 to 20 cm H₂O and PEEP at +5 cm H₂O. Subsequently, all patients were weaned to pressure support at +10 cm H₂O attaining normoventilation (PaCO₂ 36 to 44 mm Hg). Then the protocol was started with the BiPAP system or PSV in randomized chronologic order.

The first selected mode was applied for 60 min. At the end of this period, measurements were performed and the second selected mode was started. After a further 60-min period in the second mode, the same measurements were performed again. This period of 60 min is at least as long or even longer as used by others.⁵ ⁶ ⁹ During the study, changes in baseline catecholamine therapy and additional volume substitution were renounced.

Weaning Techniques

As described by Baum et al.,¹⁸ the BiPAP system is a combination of controlled ventilation and spontaneous breathing that is unrestricted in each period of the respiratory cycle. In an adjustable time sequence determining the inspiration:expiration ratio of mechanical support, the BiPAP system circuit switches between a low (Plo) and a high (Phi) airway pressure level creating a mechanical tidal volume displacement. The Phi-on-transition is synchronized with patient inspiratory efforts, switching to the Plo back again at the end of the Phi period is given by the inspiratory:expiratory ratio. At both levels of airway pressure, patients are allowed to breathe spontaneously but no additional support is given during spontaneous inspiration. With these features, the BiPAP¹⁸ system is closely similar to APRV.¹⁹ In our study, the settings of the BiPAP system were as follows: Phi=10 cm H₂O; Plo=5 cm H₂O; duration of Phi=2 s; duration of Plo=4 s resulting in an inspiration:expiration ratio of 1:2 and a mechanical respiratory frequency of 10 bpm. During PSV, spontaneous breathing is performed continuously. To compensate for the inspiratory resistance and the elevated respiratory force, each inspiration is supported by a demand flow delivered from the respiratory up to the pressure level requested.²¹ The PSV in this study was performed with a PEEP of +5 cm H₂O and the pressure support level at +10 cm H₂O. Both weaning techniques were performed with a specific ventilator (EVITA, Dräger Co, Lübeck, Germany). In both modes, maximal flow rate was 120 L/min.¹

Measurements

In each patient, a radial artery catheter (20 gauge) and a fast-response thermocatheter catheter (American Edwards Laboratory, Santa Ana, Calif.) inserted prior to the operation were used for hemodynamic measurements. This thermocatheter allows determinations of RVESV, RVEDV, and RVEF using a bedside microprocessor (REF-1, American Edwards Laboratories, Santa Ana, Calif.). Accuracy and reproducibility of this technique and validation against other methods are well documented elsewhere.²² ²⁴ Iced saline solution bolus injections (5°C) for thermocatheter measurements were performed in triplicate at end inspiration, and during ventilatory support at the end of mechanical inspiration by the BiPAP system and during PSV at the end of spontaneous breathing, into the injectate port located in the right atrium.²⁵ ²⁶ ²⁷ To take the measurements of RV peak systolic pressure (RVSPs), the pressure line was connected to the injectate port and the catheter was advanced until the ventricular pressure curve from the injectate port was obtained on the monitor. After measurements of RVSPs, the catheter was pulled back. When the injectate port was at the level of the tricuspid valve, the curve changed from the ventricular to the atrial pressure curve. The catheter was then pulled back 1 cm and was fixed. Now the injectate port was in the correct position within the right atrium, 1 to 2 cm above the tricuspid valve.²² ²⁴ ²⁵

Hemodynamic data, data on breathing pattern, and arterial blood gas measurements were recorded after 1 h in each weaning mode: heart rate (HR), mean arterial pressure (MAP), mean pulmonary artery pressure (MPAP), PCWP, central venous pressure (CVP), cardiac index (CI), RV stroke volume (RVSV), RVESV, RVEDV, RVEF, RVSPs, systemic vascular resistance index (SVRI), pulmonary vascular resistance index (PVRI), RV stroke work index (RVSWI), respiratory rate (RR), respiratory minute volume (Vexp), and tidal volume (Vexp).

Arterial blood gas analyses were performed using a blood gas analyzer (STAT profile 5, NOVA Biomedical, Waltham, Mass).

Statistical Analysis

All values are expressed as mean ± standard deviation. Statistical analysis was performed using the Wilcoxon matched pairs signed rank test. Since the aim of this study was the comparison of RV function between the BiPAP system and PSV, the parameters of primary interest in this respect were RVEF, RVEDV, RVESV, MPAP, and PVRI. For these confirmitory parameters, the significance levels were adjusted for multiple comparisons using the sequentially rejective multiple test procedure by Holm.⁶⁰ All other parameters were described by exploratory analysis, and p values <0.05 were considered significant.

RESULTS

Hemodynamic parameters representing the RV function with the BiPAP system and PSV are summarized in Table 1. In comparison to PSV, the BiPAP system resulted in a significantly higher RVESV (p=0.0017), RVEDV (p=0.0061), and in a significantly smaller RVEF (p=0.0012). The MPAP (p=0.0158) and PVRI (p=0.0355) were significantly
higher with the BiPAP system. Despite these differences, the CVP, PCWP, CI, HR, MAP, RVSV, RVSWI, RVPSP, and SVRI were not altered when weaning technique was changed (Table 2). Table 3 shows data on breathing pattern and the results of arterial blood gas analyses. Both weaning modes resulted in normoventilation and adequate oxygenation as demonstrated by similar PaO2 and PaCO2. All patients could be weaned uneventfully; extubation was performed successfully within 1 h after termination of the study.

The duration of cardiopulmonary bypass was 104 ± 37 min and aortic clamping time (ischemia)

**DISCUSSION**

In the present study, the BiPAP system and PSV were performed successfully during weaning from the respirator in 22 patients after coronary artery bypass grafting. The main finding was a small but significant increase in RVEDV and RVESV and a significant depression in RVEF, while RV afterload increased significantly with the BiPAP system compared with PSV. The similar CI during both weaning modes implies that the increase in PVRI with the BiPAP system is a primary phenomenon and not calculated from changes in flow. Both weaning modes were performed in all patients randomized; the HR, SVRI, and MAP remained unchanged and no volume substitution or changes in intravenous catecholamine therapy were performed during the study.

**Table 2—Hemodynamic Parameters During Weaning With the BiPAP System and PSV**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>BiPAP System</th>
<th>PSV</th>
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<tbody>
<tr>
<td>CI, L/min·m²</td>
<td>3.1 ± 0.7</td>
<td>3.4 ± 0.8</td>
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<tr>
<td>HR, min⁻¹</td>
<td>82.9 ± 13.9</td>
<td>83.6 ± 12.8</td>
</tr>
<tr>
<td>MAP, mm Hg</td>
<td>76.3 ± 11.6</td>
<td>74.6 ± 10.1</td>
</tr>
<tr>
<td>SVRI, dynes·s·cm⁻⁵·m²</td>
<td>1492 ± 385</td>
<td>1520 ± 524</td>
</tr>
<tr>
<td>PCWP, mm Hg</td>
<td>12.2 ± 3.9</td>
<td>12.1 ± 3.9</td>
</tr>
<tr>
<td>CVP, ml</td>
<td>11.9 ± 2.9</td>
<td>10.9 ± 2.5</td>
</tr>
<tr>
<td>RSVV, ml</td>
<td>78.9 ± 18.2</td>
<td>81.0 ± 19.2</td>
</tr>
<tr>
<td>RVPSP, mm Hg</td>
<td>34.6 ± 8.2</td>
<td>34.2 ± 7.7</td>
</tr>
<tr>
<td>RVSWI, g·m/m²</td>
<td>5.1 ± 2.8</td>
<td>4.9 ± 2.7</td>
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**Table 3—Data on Breathing Pattern and Arterial Blood Gas Measurements After 60 Min With the BiPAP System and PSV**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>BiPAP System</th>
<th>PSV</th>
</tr>
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<tbody>
<tr>
<td>RR, min⁻¹</td>
<td>13.8 ± 2.8</td>
<td>13.3 ± 3.1</td>
</tr>
<tr>
<td>Vtexp, ml</td>
<td>550 ± 155</td>
<td>615 ± 160</td>
</tr>
<tr>
<td>Vexp, L/min</td>
<td>7.59 ± 1.20</td>
<td>8.00 ± 1.28</td>
</tr>
<tr>
<td>PaO2, mm Hg</td>
<td>97.6 ± 14.6</td>
<td>97.8 ± 17.1</td>
</tr>
<tr>
<td>PaCO2, mm Hg</td>
<td>41.7 ± 3.2</td>
<td>41.9 ± 3.2</td>
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*RR=respiratory rate; Vtexp=expiratory tidal volume; Vexp= expiratory minute volume.*

Therefore, it seems unlikely to attribute the increased afterload with the BiPAP system to differences in the level of catecholamines due to different states of awareness or stress, to recovery from the postoperative depressed RV function,13,14 or to alterations in pharmacologic therapy.

Differences in cardiopulmonary function due to changes in preload and afterload have contributed to differences in the level of PEEP,1-4 in tidal volume,5 and in the inspiration:expiration ratio.6 Differences in RV afterload have also contributed to differences in ventilatory modes.7-9 In agreement with our results, APRV, which is closely similar to the BiPAP mode, was reported to cause a higher PVR compared with PSV,20 but neither RV volumes nor ejection fractions were evaluated in their study. Similar results were reported by Biondi et al9 comparing RV response on assist control ventilation, intermittent mandatory ventilation (IMV), and spontaneous breathing. During assist control ventilation, PVR was higher than during IMV and lowest during spontaneous breathing. Changes in PVR were directly related to changes in RVESV and RVSV and inversely related to changes in RVEF demonstrating the afterload dependency of RV function. Biondi et al9 concluded that RV function is more impaired during assist control ventilation compared with IMV and best preserved during spontaneous breathing. In accordance, the RV function in the present study was more impaired during the BiPAP mode, a combination of pressure-controlled ventilation and spontaneous breathing,8 compared with the spontaneous breathing in PSV. This seems to be due to the increase in RV afterload during the BiPAP mode which may be attributed to differences in the respiratory support between both modes.20

First, during PSV, the end-expiratory pressure remained constant at the PEEP of 5 cm H₂O, but the BiPAP system switches between a low (Plo) and a high (Phi) airway pressure level of 5 and 10 cm H₂O, respectively. Therefore spontaneous breathing with the BiPAP system was performed at two different pressure levels. Since the duration of Plo was 4 s and of Phi was 2 s, spontaneous breathing was performed
in one third of time at the higher pressure level of 10 cm H2O. In comparison to PSV, this period of higher pressure level may cause an increase in afterload due to an increase in mean airway pressure. With another Phi:Plo ratio and a longer Phi period constituting 80 percent of time, Valentine et al. reported a significantly higher mean airway pressure during APRV compared with PSV. They suggested this difference in airway pressure caused the increase in PVR during APRV. However, increasing levels of PEEP may contribute to an increase in RV volumes or a decrease in RVEF. This RV response was attributed to an increase in RV afterload or a decrease in RV contractility. Accordingly, Jardin et al. concluded that the impairment in RV function was the main consequence of PEEP, apparently by increasing afterload.

Second, each inspiration during PSV is supported by a demand flow up to the pressure level requested. In contrast to this mechanically assisted spontaneous breathing, switching from Plo to Phi with the BiPAP system creates a mechanical lung inflation, i.e., a controlled inspiration, similar to APRV, but not performed in PSV. This difference in inspiration may cause differences in hemodynamic response, because lung inflation by mechanical inspiration increased the RVEDV and RVESV. Jardin et al. suggested an increase in RV afterload during inspiration to cause this enlargement in RV volumes. In experimentally impaired RV function in dogs, Lucking et al. found a higher mean airway pressure during controlled ventilation compared with high-frequency ventilation, but they did not believe that this accounted for the hemodynamic differences between both ventilation modes. They speculated that the phasic changes of preload and afterload during controlled ventilation may contribute to the different hemodynamic response.

Thus, we suggest that these differences in ventilatory support between the BiPAP and PSV, i.e., the period of breathing on a higher airway pressure level and the mechanically controlled inspiration with the BiPAP system, may contribute to the increased afterload compared with PSV.

However, the increase in RV volumes with the BiPAP system compared with PSV could result from the increase in afterload, a decrease in contractility, or both. With respect to the similar RVVSP in both weaning modes, the higher volumes with the BiPAP system indicate a rightward shift of the pressure volume curve compared with PSV. This may be attributed to a decrease in contractility as suggested during inspiration by mechanical ventilation or if levels of PEEP above 15 cm H2O were applied. We cannot exclude changes in RV systolic function with the BiPAP system compared with PSV, but we did not evaluate load-independent indices of systolic function to evaluate RV contractility. It seems likely that the increase in RV volumes and the decrease in RVEF with the BiPAP system compared with PSV might be explained by a compensatory RV reaction to the increased afterload, according to the Frank-Starling mechanism. Despite the higher afterload in our patients, this mechanism was able to maintain the RV stroke work, the RVSV, and an adequate flow from the right to the left ventricle, i.e., RV pump function.

In accordance to Valentine et al., the differences in cardiovascular performance between the BiPAP system and PSV were negligible in our patients, but the lower RVEF and the higher RV volumes with the BiPAP system may indicate an encroachment on RV function with the BiPAP system compared with PSV. This may become clinically relevant in patients with a markedly depressed RV function or dilatation. Although there is no evidence in the present study, the RV dilatation may increase RV wall stress and O2 requirements while O2 supply decreases. The reduced O2 supply/demand ratio may cause RV ischemia and RV, and subsequently, left ventricular failure. Therefore, the ability to utilize the Frank-Starling mechanism seems potentially limited, especially if baseline RV function is impaired.

In contrast to the intact RV increasing levels of PEEP, volume loading or different ventilatory modes induce a more pronounced circulatory response if RV function is impaired due to myocarditis, cardiogenic shock, right coronary artery stenosis or experimental occlusion, experimental increase in RV afterload, or if RV function is impaired after extracorporeal circulation. Therefore, we might suggest that the small hemodynamic differences between the BiPAP system and PSV may become relevant in markedly impaired RV function, but further investigation is necessary to prove this speculation.

In summary, this study demonstrates that the BiPAP system compared with PSV may cause a higher RVEDV and RVESV and a depression in RVEF. In accordance with the Frank-Starling mechanism, this reaction seems to be a hemodynamic compensation to the increase in RV afterload with the BiPAP system which is attributed to differences in respiratory support created by both weaning techniques. No clinically relevant differences in hemodynamic or respiratory function were found between the BiPAP system and PSV during weaning after uneventful elective coronary artery bypass surgery.

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