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Hemodynamic Effects of Synchronized High-frequency Jet Ventilation Compared with Low-frequency Intermittent Positive-pressure Ventilation after Myocardial Revascularization

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Background: **The purpose of this prospective study was to examine the effect on cardiac performance of selective increases in airway pressure at specific points of the cardiac cycle using synchronized high-frequency jet ventilation (sync-HFJV) delivered concomitantly with each single heart beat compared with controlled mechanical ventilation in 20 hemodynamically stable, deeply sedated patients immediately after coronary artery bypass graft.**

Methods: **Five 30-min sequential ventilation periods were used interspersing controlled mechanical ventilation with sync-HFJV twice to control for time and sequencing effects. Sync-HFJV was applied using a driving pressure, which generated a tidal volume resulting in gas exchanges close to those obtained on controlled mechanical ventilation and associated with the maximal mixed venous oxygen saturation. Hemodynamic variables including cardiac output, mixed venous oxygen saturation and vascular pressures were recorded at the end of each ventilation period.**

Results: **The authors found that in 20 patients, hemodynamic changes induced by controlled mechanical ventilation and by sync-HFJV were similar. Cardiac index did not change (mean ± SD for controlled mechanical ventilation: 2.6 ± 0.7 $l \cdot min^{-1} \cdot m^{-2}$; for sync-HFJV: 2.7 ± 0.7 $l \cdot min^{-1} \cdot m^{-2}$; *P* value not significant). This observation persisted after stratification according to baseline left-ventricular contractility, as estimated by ejection fraction.**

Conclusions: **The authors conclude that after coronary artery bypass graft, if gas-exchange values are maintained within normal range, sync-HFJV does not result in more favorable hemodynamic support than controlled mechanical ventilation. These findings contrast with the beneficial effects of sync-HFJV, resulting in marked hypocapnia, on cardiac performance observed in patients with terminal left-ventricular failure. (Key words: Heart–lung interaction; human; left-ventricular afterload; mechanical ventilation; postoperative; physiology; venous return.)**

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DURING intermittent positive-pressure ventilation a decrease in cardiac output compared with spontaneous ventilation is observed in some patients.[1–3] One technique, called cardiac cycle-specific or synchronized high-frequency jet ventilation (sync-HFJV), allows the phasic effects of intermittent positive-pressure ventilation to be minimized by delivering the positive-pressure inspiration at the same point within each cardiac cycle.[4] Pinsky *et al.*[5] have demonstrated that cardiac output during sync-HFJV is less decreased than during low-frequency intermittent positive-pressure ventilation, in anesthetized patients presenting with severe left-ventricular (LV) failure waiting for cardiac transplantation. However, the beneficial effects of sync-HFJV were observed if high tidal volume was delivered, resulting in severe hypocapnia.

We designed a study to analyze the effects of sync-HFJV targeting normal blood exchanges in patients with either normal LV function or moderate LV dysfunction after elective coronary bypass graft surgery.

Patients and Methods

The study was approved by our institutional ethical committee and all patients gave written consent the day before surgery. Twenty-two nonconsecutive patients scheduled for coronary bypass graft surgery were prospectively studied. Exclusion criteria for eligibility for the study were other associated cardiac surgery or history of chronic obstructive pulmonary disease (defined as a ratio of forced expiratory volume in 1 s to forced vital capacity < 0.5 of predicted values). To account for the importance of the underlying myocardial function, we included equal numbers of patients with normal and decreased ($< 45\%$) preoperative LV ejection fraction, which was assessed before surgery by echocardiography or isotopic or angiographic ventriculography.

Perioperative Management

Antianginal therapy was discontinued the evening before surgery. One hour before surgery diazepam and morphine premedication were administrated. Oral metoprolol was also given to patients receiving chronic β-adrenergic blocker therapy. A radial artery cannula and a flow-directed modified pulmonary artery catheter (Vigilance Monitor, Baxter Edwards, Irvine, CA) capable of continuous monitoring of mixed venous oxygen saturation (Sv_{O_2}) were inserted. Anesthesia and muscle relaxation were induced and maintained with midazolam, fentanyl, and pancuronium bromide. The patient's trachea was intubated with a cuffed Hi-Lo Jet endotracheal tube (Mallinckrodt, St Louis, MO), equipped with a principal (9.0-mm inner diameter) and two auxiliary lumens (2.4-mm inner diameter each). The proximal (jet-ventilation) port opens 5 cm from the distal orifice of the endotracheal tube. The second port (for airway pressure monitoring) opens at the distal end of the endotracheal tube. A nasogastric tube and a Foley urinary catheter were also inserted. Hypothermic (28°C) cardiopulmonary bypass and cold cardioplegic–induced cardiac arrest were used. The cardiopulmonary bypass flow was set at $2\ l \cdot min^{-1} \cdot m^{-2}$ and a mean arterial pressure was maintained at 60 mm Hg using vasopressive drugs. During cardiopulmonary bypass the lungs were not ventilated but inflated with a continuous positive airway pressure of 2–5 cm H_2O. Weaning from cardiopulmonary bypass was achieved with inotropic or vasopressor drug support if required. After surgery patients were transferred to the surgical intensive care unit. Upon arrival, sedation and analgesia were provided by continuous infusion of midazolam and morphine titrated for a Ramsay score of 5.[6] The patients were placed on mechanical ventilation (Veolar ventilator; Hamilton, Rhäzüns, Switzerland). Initial ventilator settings in controlled mechanical ventilation (CMV) mode were tidal volume, 8–10 ml/kg of body weight, and respiratory rate, 12 breaths/min). Both were adjusted to maintain arterial carbon dioxide tension at 40 ± 5 mmHg. The inspired oxygen fraction was adjusted for arterial oxygen tension > 90 mmHg. Positive end-expiratory pressure of 5 cm H_2O was applied if required to obtain arterial oxygen saturation $> 93\%$. Continuous infusion of NaCl 0.9% at a rate of $5\ ml \cdot kg^{-1}$ body weight $\cdot\ h^{-1}$ was given, and additional boluses of 250 ml of the same solution were given if required to maintain pulmonary artery occlusion pressure around 10 mmHg and a cardiac output index $> 2\ l \cdot min^{-1} \cdot m^{-2}$. Body temperature, lead II electrocardiogram (ECG) and urine output were monitored throughout the postoperative period. To prevent cooling, patients were wrapped with warm blankets. The patients were observed for at least 2 h to confirm a hemodynamic steady state, which was defined as less than 10% change in hemodynamics (heart rate, cardiac output, arterial pressure), no clinically relevant bleeding, and normal body temperature. A chest radiograph was obtained and assessed before data collection to define the correct position of the endotracheal tube, pulmonary arterial and central venous catheters, surgical drains and also to confirm the absence of cardiopulmonary abnormalities (grossly enlarged mediastinal silhouette, pleural effusions, or pneumothorax). A 12-lead ECG was also recorded to document a regular sinus rhythm. Body-position changes, patient care, and endotracheal suctioning, if required, were allowed during this period but were not conducted during the study protocol.

Protocol

All studies were performed on deeply sedated patients in supine position who were not spontaneously breathing, and all pressure transducers were referenced to midchest. Sv_{O_2} was calibrated *in vivo* according to manufacturer's instruction by simultaneous measurements of mixed venous blood on a cooxymeter (Statprofile Ultra, Nova Biomedical, Waltham, MA). For the first 10 patients hemodynamic variables and airway pressure were continuously recorded on a strip-chart paper recorder. For the last 10 patients hemodynamic data were recorded intermittently using a central monitoring station (Hewlett-Packard VECTRA 712/60, Palo Alto, CA).

Study Protocol. The study protocol consisted of five sequential ventilatory steps of 30 min each: CMV_1, sync-$HFJV_1$, CMV_2, sync-$HFJV_2$, and CMV_3. CMV_1 was set to maintain adequate arterial blood gases. CMV_2 and CMV_3 settings were kept identical to CMV_1 and served as time and sequence control steps. Peak airway pressure was kept below 25 cm H_2O during CMV by changing first inspiratory-to-expiratory ratio from 1:2 to 1:1, then by decreasing tidal volume. Sync-HFJV was delivered with no entrainment of bias flow and with passive exhalation using an Acutronic (Jona, Switzerland) AMS-1000 ventilator (driving pressure 1.8 psi; inspiratory-to-expiratory ratio 30:70, inspired oxygen fraction for arterial oxygen tension $>$ 90 mm Hg). Synch-$HFJV_1$ and sync-$HFJV_2$ were generated by synchronizing the HFJV inspiration phase with the QRS complex of the ECG, as previously described.[4,5] Briefly, the QRS signal from the ECG monitor was used to trigger the ventilator. A variable-delay circuit between the ECG signal and the ventilator enabled timing of the jet inspiratory pulse from the early systolic to the late diastolic phase of the arterial pressure pulse. The optimal timing of the jet inspiratory pulse delivery was established at the beginning of each sync-HFJV run by delaying by 10% the ECG R-wave trigger jet pulse delivery through the cardiac cycle and observing the resultant steady state Sv_{O_2} value (fig. 1). Sync-HFJV timing corresponding to the highest Sv_{O_2} value was used for the sync-$HFJV_1$ and sync-$HFJV_2$ steps. Sv_{O_2} variation was chosen instead of the continuous cardiac output value because the former varies more rapidly than the second and represents a real online continuous monitoring.

Data Recording. At the end of each period, body temperature Sv_{O_2}, heart rate, systolic, diastolic, and mean arterial and pulmonary arterial pressures, pulmonary artery occlusion, and central venous pressures were recorded from the bedside monitor (M1166A; Hewlett-Packard). Mean cardiac output was estimated by averaging triplicate injections of 10 ml ambient-temperature 0.9% NaCl delivered randomly during the respiratory cycle. At the end of each study period arterial and mixed venous blood gases were simultaneously measured (Statprofile Ultra, Nova Biomedical), and standard calculated variables were obtained from blood-gas data. Ventilator settings (respiratory rate, tidal volume, inspiratory-to-expiratory ratio, inspired oxygen fraction, positive end-expiratory pressure) and peak and mean airway pressures were also recorded.

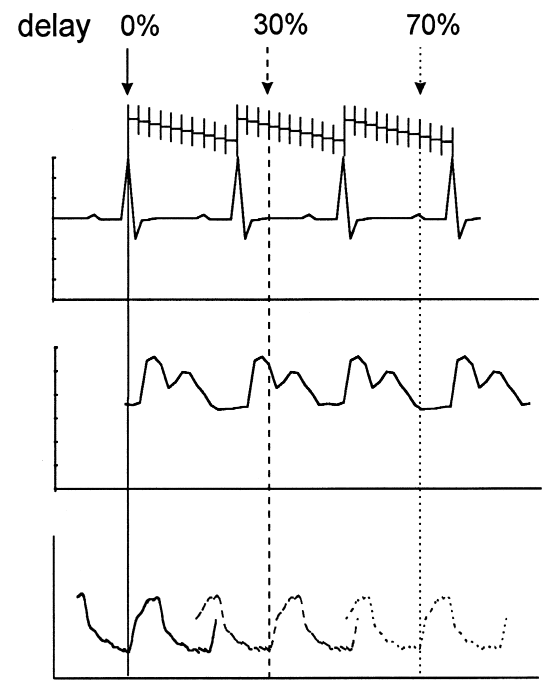

Fig. 1. Schematic representation displaying simultaneous electrocardiogram, arterial pressure, and airway pressure waves. One entire cardiac cycle is encompassed between an electrocardiographic R-R interval. A computerized interface allows division of this R-R interval into 10 equal portions. Jet air pulse can be delivered at any chosen delay. Three different delays (0, 30, and 70% from R-R interval) are shown.

Statistical Analysis. The data were analyzed using Graph Pad Instat software (version 2.05a; Graph Pad software, San Diego, CA) for a personal computer. In order to confirm the steady-state condition, a one-way repeated-measures analysis of variances was performed to compare data for the three CMV steps. Data for CMV_1 and CMV_2 and respectively sync-$HFJV_1$ and sync-$HFJV_2$ were then pooled, and a two-tailed paired t test was used. Comparisons between sync-HFJV and the preceding CMV run in two subsets of patients stratified by baseline level of LV contractility according to their preoperative LV ejection fraction (impaired LV function group, LV ejection fraction $<$ 45%; normal LV function group, LV ejection fraction $\geq$ 45%) were performed by two-tailed paired t test. All values are expressed as mean $\pm$ SD, and $P < 0.05$ was considered statistically significant.

Results

Among patients who gave informed consent, two were excluded before starting the study protocol. The first

Table 1. Demographic and Preoperative Characteristics

	Mean ± SD (n = 20)	Range	No. of Patients
Age (yr)	67 ± 10	43–80	
Sex (female/male)	4/16		
Weight (kg)	79 ± 13	53–110	
Height (cm)	169 ± 9	153–180	
LVEF (%)	45 ± 11	25–60	
Associated diseases			
Diabetes			6
MI > 6 months			10
MI < 6 months			6
Hypertension			9
Concomitant cardiac medications			
Nitrates			19
β-adrenergic blockers			4
Calcium channel blockers			3
Aspirin			14
ACE inhibitors			9
Digitalis			4
Diuretics			6

LVEF = left ventricular ejection fraction; MI = myocardial infarction; ACE = angiotensin converting enzyme.

one required reoperation for surgical hemostasis because of ongoing hemorrhage, and the second patient had unstable hemodynamics. Twenty patients were included in the final analysis, and all of them tolerated the experimental protocol well. Demographic and preoperative characteristics are presented in table 1. Overall LV ejection fraction was 45 ± 11%. Patients in the low LV ejection fraction group (n = 10) had an average ejection fraction of 35 ± 6%; in the normal LV ejection fraction group (n = 10) the fraction was 54 ± 6%. An average of three (range, two to four) coronary artery bypasses were performed, with all patients but one having an internal mammary artery graft. The mean cardiopulmonary bypass duration was 140 ± 32 min, and the aortic cross-clamping time was 84 ± 20 min. Catecholamine infusion was required in 14 patients for cardiopulmonary bypass weaning (dobutamine, n = 13, and/or epinephrine, n = 2). At SICU arrival, two patients were receiving continuous intravenous infusions of dobutamine (5 $\mu g \cdot kg^{-1} \cdot min^{-1}$), and one patient of epinephrine (0.1 $\mu g \cdot kg^{-1} \cdot min^{-1}$). Continuous intravenous infusion of nifedipine at a rate of 5 mg/h was given to an additional patient. In these four patients, vasoactive infusion rates were kept constant during the study protocol.

Ventilatory settings, airway pressures, and gas-exchange values are shown in table 2, and hemodynamic variables are presented in table 3. The steady-state assessment of the three different CMV runs showed a significant difference in mean arterial pressure between CMV_1 and both other CMV runs and in systemic vascular resistance between CMV_1 and CMV_3. Other differences among the three CMV runs were minimal and not clinically relevant. During the sync-HFJV runs (pooling data from both runs) the optimal Sv_{O_2} was obtained during the early diastolic period in 7 runs, during the late diastolic in 5, during the early systolic in 17, and during the late systolic period in 11. No significant difference was observed between the best Sv_{O_2} obtained by delay-

Table 2. Pooled Data of the Ventilatory Setting, Airway Pressure and Blood Gases Measured at the End of the Different Ventilatory Periods

	CMV	HFJV
RR (breaths/min)	11 ± 2	88 ± 21*
V_T (ml)	679 ± 68	—
Driving pressure (bar)	—	1.6 ± 0.2
I/E ratio	0.7 ± 0.3	0.3 ± 0.0*
P_{aw} peak (mmHg)	19 ± 5	7 ± 2*
P_{aw} mean (mmHg)	6.1 ± 2.5	3.5 ± 2.5*
pH	7.39 ± 0.06	7.42 ± 0.07*
Pa_{CO_2} (mmHg)	35 ± 5	32 ± 7*
Pa_{O_2}/FI_{O_2} (mmHg)	277 ± 57	223 ± 67*

Data are mean ± SD; n = 20.

RR = respiratory rate; V_T = tidal volume; I/E ratio = inspiratory-to-expiratory ratio; P_{aw} = airway pressure; CMV = controlled mechanical ventilation; HFJV = high-frequency jet ventilation; Pa_{CO_2} = carbon dioxide partial pressure; Pa_{O_2} = oxygen partial pressure; FI_{O_2} = fraction of inspired oxygen.

* $P < 0.05$ compared with CMV.

Table 3. Hemodynamic Variables Measured at the End of the Different Ventilatory Periods

	CMV	HFJV
Temperature (°C)	36.9 ± 0.7	37.0 ± 0.7*
HR (beats/min)	91 ± 16	91 ± 16
MAP (mmHg)	73 ± 11	74 ± 13
MPAP (mmHg)	20 ± 6	21 ± 6*
CVP (mmHg)	9 ± 3	9 ± 3
PAOP (mmHg)	11 ± 4	11 ± 3
CI ($l \cdot min^{-1} \cdot m^{-2}$)	2.6 ± 0.7	2.7 ± 0.7
SVR ($dyne \cdot s^{-1} \cdot cm^{-5}$)	2084 ± 684	2067 ± 685
PVR ($dyne \cdot sec^{-1} \cdot cm^{-5}$)	267 ± 112	302 ± 121*
SV_{O_2} (%)	64 ± 8	62 ± 8*
Q_S/Q_T (%)	28 ± 6	29 ± 7
(a-v) D_{O_2} (ml/%)	5.0 ± 1.1	5.1 ± 1.2
O_2 extraction (%)	36 ± 8	38 ± 9*
D_{O_2} (ml/min)	694 ± 180	704 ± 194

Data are mean ± SD; n = 20.

HR = heart rate; MAP = mean arterial pressure; MPAP = mean pulmonary artery pressure; CVP = central venous pressure; PAOP = pulmonary artery occlusion pressure; CI = cardiac index; SVR = systemic vascular resistance; PVR = pulmonary vascular resistance; SV_{O_2} = mixed venous oxygen saturation; Q_S/Q_T venous admixture; (a-v) D_{O_2} = difference in arteriovenous oxygen content; D_{O_2} = oxygen delivery.

* $P < 0.05$ compared with CMV.

Table 4. Hemodynamic Variables at the End of the Different Ventilatory Periods in Patients with a Preoperative Left-ventricular Ejection Fraction > 45%

	CMV_1	$HFJV_1$	CMV_2	$HFJV_2$
HR (beats/min)	90 ± 15*†	87 ± 15	85 ± 15	84 ± 15
CI ($l \cdot min^{-1} \cdot m^{-2}$)	2.5 ± 0.6	2.5 ± 0.6	2.4 ± 0.6	2.6 ± 0.7
PAOP (mmHg)	9 ± 4	10 ± 4	10 ± 4	11 ± 3
Sv_{O_2} (%)	63 ± 8*	59 ± 9	60 ± 8*	59 ± 8
Q_S/Q_T (%)	27 ± 5	27 ± 6	26 ± 5	26 ± 6
(a-v)D_{O_2} (ml/%)	5.0 ± 1.1*†	5.4 ± 1.2	5.4 ± 1.2*	5.5 ± 1.1
O_2 extraction (%)	37 ± 8*	40 ± 10	40 ± 9*	41 ± 9
D_{O_2} (ml/min)	658 ± 179	635 ± 185	632 ± 194	702 ± 234

Data are mean ± SD; n = 10.

For an explanation of abbreviated terms, see Table 3.

* $P < 0.05$ compared the following ventilatory mode.

† $P < 0.05$ CMV_1 compared with CMV.

ing the jet pulse of sync-HFJV runs in patients with preoperative normal or impaired systolic LV function. Tables 4 and 5 present the hemodynamic data separated by the 45% LV ejection fraction cut-off. Figure 2 shows individual changes in cardiac index induced by the ventilatory mode switch from CMV (CMV_1 and CMV_2, respectively) to HFJV (sync-$HFJV_1$ and sync-$HFJV_2$, respectively) and after return to CMV (CMV_2 and CMV_3, respectively). A wide variability of the response was observed among patients, and separating patients into two groups according to their preoperative LV ejection fraction did not modify individual variability.

Discussion

Our data show that, unlike patients with severe congestive cardiomyopathy awaiting cardiac transplantation, patients with less severely compromised global myocardial function after cardiac revascularization surgery did not demonstrate hemodynamic improvement if airway pressure was synchronized with the cardiac cycle and normal blood-exchange values were targeted, avoiding severe hypocapnia. Indeed, no differences in cardiac output were observed if sync-HFJV was compared with CMV in our study, even if the timing of the jet pulse delivery was adjusted according to the individual best obtained value of mixed venous oxygen saturation. The absence of hemodynamic improvement was observed even though the majority of patients exhibited the highest mixed venous oxygen saturation value during the systolic or at the end of the diastolic phase (33/40 sync-HFJV runs), when minimal effect of the increase in intrathoracic pressure is expected on the venous return during the cardiac cycle.

Different results have been reported concerning the hemodynamic effects of sync-HFJV both in experimental and human studies.[7–20] The discrepancy in the response is probably related to the different basal conditions of

Table 5. Hemodynamic Variables at the End of the Different Ventilatory Periods in Patients with a Preoperative Left-ventricular Ejection Fraction < 45%

	CMV_1	$HFJV_1$	CMV_2	$HFJV_2$
HR (beats/min)	97 ± 18	96 ± 14	94 ± 17	96 ± 17
CI ($l \cdot min^{-1} \cdot m^{-2}$)	2.8 ± 0.7	2.9 ± 0.8	2.8 ± 0.8	2.8 ± 0.7
PAOP (mmHg)	13 ± 4	13 ± 4	13 ± 4	12 ± 2
SV_{O_2} (%)	67 ± 6	64 ± 9	65 ± 7	64 ± 6
Q_S/Q_T (%)	29 ± 6*	33 ± 6*	30 ± 7	30 ± 7
(a-v) D_{O_2} (ml/%)	4.8 ± 1.1	4.6 ± 1.2	4.9 ± 1.1	5.0 ± 1.3
O_2 extraction (%)	34 ± 6	34 ± 9	34 ± 7	35 ± 7
D_{O_2} (ml/min)	733 ± 193	738 ± 217	715 ± 174	722 ± 178

Data are mean ± SD; n = 10.

For an explanation of abbreviated terms, see Table 3.

* $P < 0.05$ compared with the following ventilatory mode.

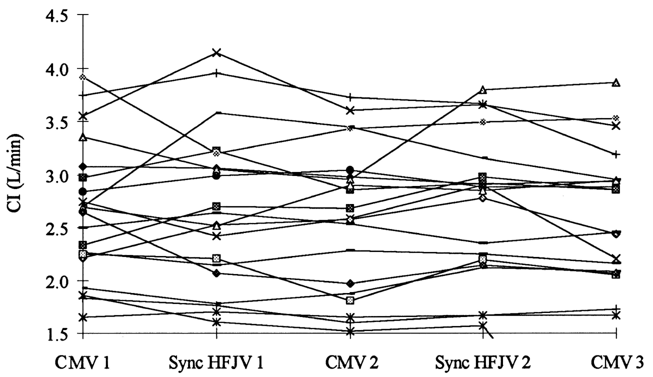

Fig. 2. Individual changes in mean cardiac index induced by switching from controlled mechanical ventilation to synchronized high-frequency jet ventilation and returning back to controlled mechanical ventilation.

heart function and circulation state rather than changes in heart–lung interactions. However, our results are in accordance with those of Bayly *et al.*,[21] who did not find a significant difference between low-frequency intermittent positive-pressure ventilation and sync-HFJV in 10 stable patients without heart failure, but they contrast with findings from Pinsky *et al.*[5] and Angus *et al.*[22] Different hypotheses may be advanced to explain the absence of improvement in our patients. In our study we targeted a normal blood-gas exchange guided by standard clinical practice criteria, avoiding the marked hypocapnia obtained in the study by Pinsky *et al.*[5] This may have two different simultaneous consequences. The driving pressure used to deliver the HFJV tidal volume was kept at the lowest value sufficient to provide efficient gas exchange, possibly mitigating the advantage of cardiac cycle–related increases in intrathoracic pressure on the pressure gradient for LV ejection. Furthermore, a relatively low tidal volume was delivered during the CMV runs (around 8 ml/kg body weight) to obtain normal blood exchanges during conventional ventilation. The beneficial effect of synchronized HFJV might have been minimized by the reduced tidal volume ventilation during CMV. Thus, the low peak and mean airway pressures generated during all steps of the protocol may have contributed to minimize the negative effect of intrathoracic pressure swings on LV output. Another possible explanation for the lack of a differential effect of synchronized HFJV could be related to the surgical procedure. Indeed, the pericardium was left open anteriorly at the end of surgery. This may have modified the interaction between airway pressure oscillation transmission and the effective pericardial pressure. The relationship between pleural and pericardial pressures may have been further affected by a decreased lung compliance secondary to fluid accumulation in the lungs after cardiopulmonary bypass. Finally, a transient positive effect of sync-HFJV could have occurred initially but been attenuated by the intact feedback mechanisms provided by arterial baroreceptors of the great arteries. We doubt that this is the case, because we would have expected mixed venous oxygen saturation to initially decrease with the initiation of sync-HFJV and then increase toward pre–sync-HFJV values. We did not observe such temporal behavior in mixed venous oxygen saturation.

In conclusion, after coronary artery bypass graft surgery, synchronized HFJV provides no hemodynamic advantage compared with CMV.

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References

1. Buda AJ, Pinsky MR, Ingels NB Jr, Daughters GTD, Stinson EB, Alderman EL: Effect of intrathoracic pressure on left ventricular performance. N Engl J Med 1979; 301:453–9

2. Pinsky MR: Instantaneous venous return curves in an intact canine preparation. J Appl Physiol 1984; 56:765–71

3. Cournand A, Motley H, Werko L, Richards D: Physiologic studies of the effects of intermittent positive pressure breathing on cardiac output in man. Am J Physiol 1948; 152:162–74

4. Pinsky MR, Matuschak GM, Bernardi L, Klain M: Hemodynamic effects of cardiac cycle-specific increases in intrathoracic pressure. J Appl Physiol 1986; 60:604–12

5. Pinsky MR, Marquez J, Martin D, Klain M: Ventricular assist by cardiac cycle-specific increases in intrathoracic pressure. Chest 1987; 91:709–15

6. Ramsay MA, Savege TM, Simpson BR, Goodwin R: Controlled sedation with alphaxalone-alphadolone. Br Med J 1974; 2:656–9

7. Fusciardi J, Rouby JJ, Barakat T, Mal H, Godet G, Viars P: Hemodynamic effects of high-frequency jet ventilation in patients with and without circulatory shock. Anesthesiology 1986; 65:485–91

8. Normandale J, Patrick M, Sherry KM, Feneck RO: Comparison of conventional intermittent positive pressure ventilation with high frequency jet ventilation: Studies following aortocoronary bypass graft surgery. Anaesthesia 1987; 42:824–34

9. Crimi G, Conti G, Bufi M, Antonelli M, de Blasi RA, Mattia C, Romano R, Gasparetto A: High frequency jet ventilation (HFJV) has no better haemodynamic tolerance than controlled mechanical ventilation (CMV) in cardiogenic shock. Intensive Care Med 1988; 14:359–63

10. Courtney SE, Spohn WA, Weber KR, Miles DS, Gotshall RW, Wong RC: Cardiopulmonary effects of high frequency positive-pressure ventilation versus jet ventilation in respiratory failure. Am Rev Respir Dis 1989; 139:504–12

11. Goto K, Goto H, Benson KT, Unruh GK, Arakawa K: Efficacy of high-frequency jet ventilation in cardiac tamponade. Anesth Analg 1990; 70:375–81

12. Guimond JG, Pinsky MR, Matuschak GM: Effect of synchronous increase in intrathoracic pressure on cardiac performance during acute endotoxemia. J Appl Physiol 1990; 69:1502–8

13. Hayes JK, Smith KW, Port JD, Jordan WS: Comparison of tidal ventilation and high-frequency jet ventilation before and after cardiopulmonary bypass in dogs using two-dimensional transesophageal echocardiography. J Cardiothorac Vasc Anesth 1991; 5:320–6

14. Heres EK, Shulman MS, Krenis LJ, Moon R: High-frequency ventilation with a conventional anesthetic ventilator during cardiac surgery. J Cardiothorac Vasc Anesth 1995; 9:63–5

15. Matuschak GM, Pinsky MR, Klain M: Hemodynamic effects of synchronous high-frequency jet ventilation during acute hypovolemia. J Appl Physiol 1986; 61:44–53

16. Mitzner W, Gioia F, Weinmann GG, Robotham JL, Ehrlich W: Interaction between high frequency jet ventilation and cardiovascular function. Ann Biomed Eng 1987; 15:319–29

17. Schulman DS, Biondi JW, Bell L, Rutlen DL: Hemodynamic effects of 1:2 ECG-coupled jet ventilation in the dog: A comparison with other modes. Am Rev Respir Dis 1991; 144:819–25

18. Sherry KM, Windsor JP, Feneck RO: Comparison of the haemodynamic effects of intermittent positive pressure ventilation with high frequency jet ventilation: Studies following valvular heart surgery. Anaesthesia 1987; 42:1276–83

19. Tabatabai M, Javadi PP: Comparison of cardiopulmonary variables with intermittent positive pressure ventilation and high-frequency jet ventilation during abdominal aortic operations. Eur Surg Res 1989; 21:274–9

20. Traverse JH, Korvenranta H, Carlo WA: Effect of ventilatory strategy on cardiac output during high frequency jet ventilation. Cardiovasc Res 1991; 25:309–13

21. Bayly R, Sladen A, Guntupalli K, Klain M: Synchronous versus nonsynchronous high-frequency jet ventilation: Effects on cardiorespiratory variables and airway pressures in postoperative patients. Crit Care Med 1987; 15:915–7

22. Angus DC, Lidsky NM, Dotterweich LM, Pinsky MR: The influence of high-frequency jet ventilation with varying cardiac-cycle specific synchronization on cardiac output in ARDS. Chest 1997; 112:1600–6