

High-Frequency Percussive Ventilation: A New Strategy for Separation from Extracorporeal Membrane Oxygenation

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We report the case of a 48-year-old woman who developed severe septic shock and lung injury after community-acquired pneumonia. She was supported on arteriovenous extracorporeal membrane oxygenation (ECMO) for 19 days. To facilitate decannulation and separation from ECMO, we began trials of high-frequency percussive ventilation (HFPV) using the volumetric diffusive respiration ventilator VDR-4 (Percussionaire Corp, Sandpoint, Idaho) for 4 consecutive days (1 before and 3 after). Decannulation was achieved successfully, and the patient was transferred to the floor 3 months later. During the 4 days of HFPV, the chest radiograph improved, as did gas exchange and clearance of pulmonary secretions. HFPV may be a promising strategy for improving lung recruitment and airway clearance during separation from ECMO in the critically ill patient. (A&A Case Reports. 2015;4:79–84.)

In patients with severe, refractory acute respiratory distress syndrome (ARDS), the combination of lung rest with extracorporeal membrane oxygenation (ECMO) and high-frequency percussive ventilation (HFPV) has been advocated as a potential therapeutic option.^{1–5} Proposed advantages of HFPV include improved oxygenation and ventilation at lower peak mean and end-expiratory pressures compared with those associated with conventional ventilation.^{6–9}

CASE DESCRIPTION

The patient was a 48-year-old 70-kg woman admitted to our emergency room with severe right lung pneumonia (Fig. 1). She was initially treated with bilevel positive airway pressure (pressure support ventilation [PSV] +12 cm H₂O and positive end-expiratory pressure [PEEP] +8 cm H₂O, F_{ro} 1) but continued to deteriorate clinically. Blood gas analysis showing severe metabolic and respiratory acidosis (oxyhemoglobin saturation-SpO₂ 76%, pH 6.78, Pao₂ 61 mm Hg, Paco₂ 69 mm Hg, base excess –16.2 mEq/L, HCO₃ 16.2 mmol/L) was obtained, and she was transferred to the intensive care unit (ICU) for further management.

In the ICU, her trachea was intubated, and her lungs were initially ventilated using pressure control ventilation (PCV) to maintain tidal volume (TV) = 6 mL/kg and peak inspiratory pressure (PIP) ≤30 cm H₂O (PEEP +12 cm H₂O, PCV +18 cm H₂O, F_{ro} 1.0, and respiratory rate 37 breaths/min). A postintubation blood gas analysis demonstrated only slight improvement (pH 7.05, Pao₂ 79 mm Hg, Paco₂ 57 mm Hg). Upon admission

to the ICU, her status was categorized as severe septic shock with worsening oxygenation and hemodynamic instability (Table 1). Because of persistent hypotension (80/50 mm Hg, 130 bpm), we also immediately administered 2-L IV crystalloid over the next hour with limited response.

Inotropic support with epinephrine and dobutamine (for 72 hours) and norepinephrine (for 14 days) was started, and cardiac output was monitored using the Pulsion PICCO (Pulsion Medical Systems AG, Munich, Germany).

After 2 days with persistent hypoxemia and hypotension despite maximal ventilation (pH 7.3, Pao₂ 58 mm Hg, F_{ro} 1, Pco₂ 48, base excess –7 mEq/L, 85/45 mm Hg, and



Figure 1. Anteroposterior chest radiograph after admission shows a right pneumonia.

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Table 1. Hemodynamics, ABGs, Vasoactive Drugs During the First 48 Hours

	Day 1	Day 2 before AV ECMO	Day 2 after AV ECMO
Hemodynamics	CI 1.7 L/min/m ² , SVV 40%, MAP 66 mm Hg, 140 h, SVRI 950 dyn*s*cm ⁻⁵ *m ² (pulsion PICCO)	CI 1.6 L/min/m ² , SVV 30%, MAP 56 mm Hg, 110 h, SVRI 900 dyn*s*cm ⁻⁵ *m ² (pulsion PICCO)	AV ECMO setting, RPM 4100RPM, 4.7 L/min, Gas flow (L) 2, FiO ₂ 0.6 (+CV 1 FiO ₂)
PaO ₂ /FiO ₂	0.7	0.5	>1.5
Sato ₂ (%)	88	90	97
Inotropic agents	Norepinephrine 0.25 mcg/kg/min, epinephrine 0.1 mcg/kg/min	Norepinephrine 0.45 mcg/kg/min, epinephrine 0.06 mcg/kg/min	Norepinephrine 0.1 mcg/kg/min
Diuresis	Absent	Absent	CVVH

Pulsion PICCO was used for the first 2 days. After that, we used transthoracic echocardiograms frequently and MostCare occasionally (after decannulation). Norepinephrine was stopped at day 3, and dobutamine was started.

CI = cardiac index; SVV = stroke volume variation; MAP = mean arterial blood pressure; HR = heart rate; SVRI = systemic vascular resistance index; CV = conventional ventilation; CVVH = continuous venovenous hemofiltration; ABGs = arterial blood gases; RPM = rates per minute.

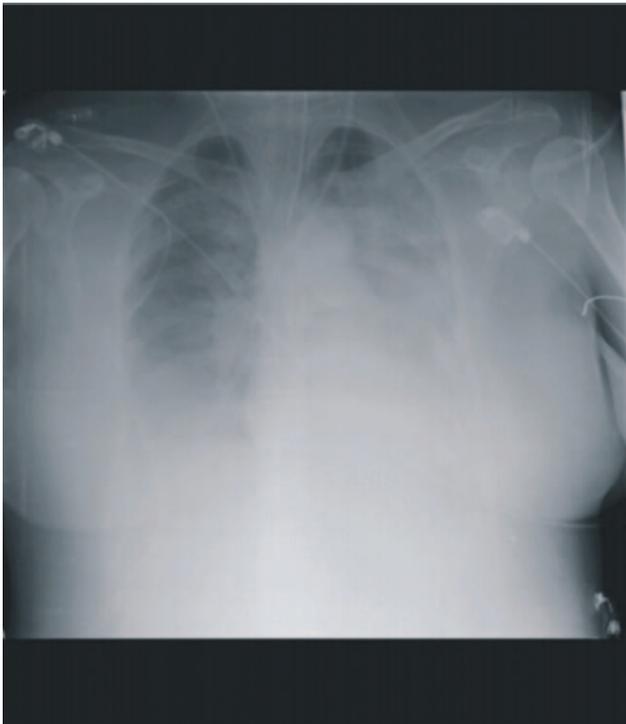


Figure 2. Chest radiograph 6 days after admission, on arteriovenous extracorporeal membrane oxygenation (ECMO), shows pulmonary infiltrates and ground-glass aspect on both lungs.



Figure 3. Computed tomography scan before decannulation still shows right pulmonary infiltrates and left “consolidation.”

120 bpm; Fig. 2), we introduced arteriovenous ECMO to allow lung rest and provide hemodynamic support. The PICCO device was removed.

During the next 16 days, the patient was treated with antibiotics and steroids for *Klebsiella pneumoniae*; she developed renal failure and was treated by continuous venovenous hemofiltration after which she improved slightly. Her lungs were ventilated during the first 3 days in the ICU with PCV 20±2 cm H₂O, PEEP 12±2 cm H₂O, and high FiO₂ during and then PSV 20±2 cm H₂O, PEEP 12±2 cm H₂O, and lower FiO₂. We used smaller TVs (6–8 mL/kg of predicted body weight) and a higher level of PEEP when the patient was receiving ECMO to reduce repetitive overstretching or collapse of lung units with each respiratory cycle, which can generate local and

systemic inflammation, contributing to multiorgan failure and death.^{10–14}

Her white blood cell count decreased from 32 to 8×10⁹/L, and inotropic drugs were gradually decreased and eliminated by ECMO on day 14. However, despite adequate organ perfusion and oxygenation with ECMO, radiographic imaging continued to show diffuse ARDS. A computed tomography scan performed on day 15 showed multiple pulmonary infiltrates, atelectasis, and ground-glass opacity of the right lung (Fig. 3), whereas the left lung was completely consolidated.¹⁵ In addition, her course was complicated by difficult pulmonary toilet because of thick secretions and frequent left-sided hemoptysis, which was treated with bronchoscopic lavage and antifibrinolytic medication (tranexamic acid). On day 16, she began to develop complications of ECMO

Table 2. Oxygenation and ECMO Changes During the First HFPV Trial

	Oxygenation and ECMO setting		
	CV	2 h after HFPV	4 h after HFPV
pH	7.41	7.52	7.5
Pao ₂ (mm Hg)	96	154	124
Paco ₂ (mm Hg)	42	32	31
Sato ₂ (%)	97.7	99.5	99.5
RPM	2700	2800	2330
L/min	2	1.8	1.8
Gas flow (L)	2.8	1	1
Fio ₂	0.7	0.5	0.5

Pao₂ increased from 96–124 mm Hg, with a lower fractional inspiratory oxygen (Fio₂). There was no variation with hemodynamic parameters during HFPV. Heart rate and mean arterial blood pressure were stable. The main variations were correlated to ECMO support and oxygenation.

CV = conventional ventilation; ECMO = extracorporeal membrane oxygenation; HFPV = high-frequency percussive ventilation; RPM = rates per minute.

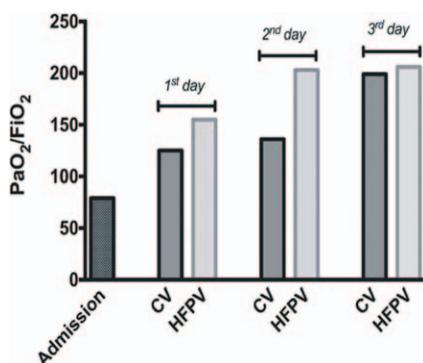


Figure 4. Arterial pressure of oxygen increasing during high-frequency percussive ventilation (HFPV) treatment after decannulation. Measurements were recorded during conventional ventilation (CV) and after 2 hours of HFPV. The improvement in PaO₂/Fio₂ was significant and important after each daily trial.

and anticoagulation such as inadequate oxygenation and lower extremity edema.¹⁶

The patient was tracheostomized on day 18. Because of increasing ECMO-related complications, we began HFPV to accelerate the rate of lung recovery and allow for transition off ECMO.^{16–18}

We began with a 4-hour HFPV trial with the hope that clearance of bronchial and peripheral secretions would improve.^{6,19,20} Within the first 20 minutes on HFPV, there was improved clearance of secretions (as measured by a need for more frequent suctioning, every 20 minutes vs 2–4 hours on conventional ventilation, and a larger volume of suctioned secretions) and a reduced requirement for ECMO support.

During this first HFPV trial, the patient remained on ECMO, and the volumetric diffusive respiration ventilator setting was convective PEEP of +14 cm H₂O, convective PIP of +34 cm H₂O for the first 2 hours (increased to +35 cm H₂O later), convective rate of 8/min, inspiratory-expiratory (I:E) rate of 1.5:1 increased later to 2.1:1, and Fio₂ 0.8 decreased later to 0.75 (Table 2).

Arterial blood gas analysis showed improved oxygenation 2 and 4 hours after the HFPV session, with no requirement for inotropic drugs during the HFPV period (Fig. 4).

After the HFPV period, conventional ventilation was restarted, and the patient's lungs were ventilated overnight using PSV +20 cm H₂O (+2 PCV-synchronized intermittent mandatory ventilation), PEEP +12 cm H₂O, PIP around +30 cm H₂O, and Fio₂ 0.7.

The next day, we discontinued ECMO because its oxygenation and hemodynamic support were minimal, and we preferred to avoid new complications. Daily sessions of HFPV for 2 h/d were continued for 3 more days.

On the first day without ECMO, a HFPV trial was begun with 680/min percussive rate; a convective rate of 14/min; PEEP +14 cm H₂O; with these settings, PIP +32 cm H₂O; 1.4:1 I:E and Fio₂ 0.7.

On the second day, a slightly lower HFPV rate of 670/min and a convective rate of 13/min were used, with PEEP = 13 cm H₂O; with these settings, PIP = 40 cm H₂O, 1.5:1 I:E, and Fio₂ 1.

On the third day, HFPV was repeated with a 670/min percussive rate and a convective rate of 9/min; PEEP = +14 cm H₂O; with these settings, PIP = 42 cm H₂O; 2.1:1 I:E and Fio₂ 0.5 (Table 3).

After each trial, the lungs were ventilated using conventional ventilation as above, but pressure support and Fio₂ were progressively reduced (our targets were pH 7.35–7.45, physiologic range for Pco₂ and PaO₂/Fio₂ 150–200).

Upon initiation of HFPV each day, we consistently observed an improvement in oxygenation, with the PaO₂/Fio₂ ratio increasing from 141 ± 16 to 228 ± 28.8 in 3 days (Table 3). Figure 4 shows changes in PaO₂/Fio₂ after each HFPV daily trial and (for comparison) on admission to the ICU.

We also found improved lung compliance after each HFPV trial. After 1 HFPV session, TV increased from 430 to 560 mL, with inspiratory PSV requirements decreasing from 20 to 18 mm Hg and lower Fio₂ from 0.7 to 0.6. This observation may have been attributable to improved mobilization and clearance of secretions. We observed a need for more frequent suctioning and a larger volume of suctioned secretions after each HFPV trial. Improvements in pulmonary compliance and gas exchange persisted for up to 3 days after HFPV trials (Fig. 5).

One month after tracheostomy decannulation, a chest computed tomography scan revealed a reduction in bilateral pulmonary infiltrates, atelectasis, and a significant pulmonary recruitment (Fig. 6). Ground-glass aspect was reduced, and aeration of lungs improved. Both lungs were almost completely expanded.

The improvement in lung aeration, evidenced by follow-up chest radiographs (Fig. 7, A and B), physical examination findings, and increased Pao₂, was maintained until the patient's transfer to the general inpatient ward, during which she was breathing spontaneously on room air at 3 months after ICU admission.

DISCUSSION

HFPV is a form of high-frequency ventilation that improves gas exchange by delivering low TV, breaths at high frequencies to enhance alveolar gas mixing by multiple mechanisms, including convective flow, asymmetric velocity profiles, Taylor dispersion, molecular diffusion, cardiogenic mixing, and pendelluft.²¹

Table 3. Oxygenation and High-Frequency Percussive Ventilation Settings

	First day without ECMO	2h after HFPV	Second day without ECMO	2h after HFPV	Third day without ECMO	2h after HFPV
Oxygenation pre-HFPV and post-HFPV						
pH	7.37	7.4	7.35	7.52	7.39	7.36
Pao ₂ (mm Hg)	88.8	109.6	95.1	203	119.9	103.1
Paco ₂ (mm Hg)	46.6	41.6	47.2	31.1	43.7	45.5
Sato ₂ (%)	97	98.1	97.9	99.8	99	98.4
Pao ₂ /Fio ₂	141±16	184±28	136.5±0.5	191±11.5	214.5±15.5	228±28.8
HFPV settings						
Percussive rate (rate/min)		680		670		670
Convective rate (rate/min)		14		13		9
PEEP (cm H ₂ O)		14		11		14
PIP (cm H ₂ O)		32		40		42
I:E		1.4:1		1.5:1		2.1:1
Fio ₂		0.7		1		0.5

Pao₂/Fio₂ rose from 141±16 to 228±28.8 after 3 days of HFPV. Paco₂ and pH did not change significantly. The high peak inspiratory pressure (PIP) level does not indicate a very high pressure level because the sample point is on the patient, directly connected with the tracheotomy. PIP at the carina is approximately one-third the level set on the HFPV. In the conventional ventilator, the sampling point is inside the ventilator >1 m away from the patient.¹³

HFPV = High-Frequency Percussive Ventilation; ECMO = extracorporeal membrane oxygenation; positive end-expiratory pressure;

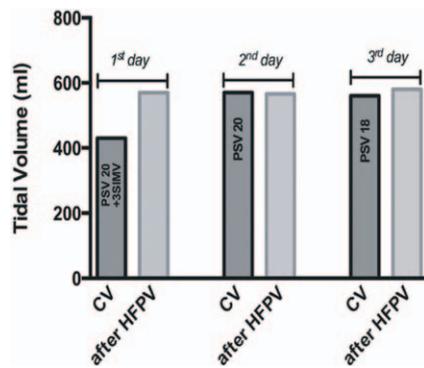


Figure 5. Tidal volume (TV) variation during high-frequency percussive ventilation (HFPV). TV was recorded before disconnection from conventional ventilation (CV) and after 2 hours of HFPV (using the same ventilator setting). An improvement in lung recruitment was noticed after the first trial. Pressure support ventilation was also reduced day by day.

In cases of pneumonia, HFPV may further augment gas exchange by dispersing inspissated secretions. Two possible mechanisms may facilitate mucus clearance: an increased mucus flow interaction leading to decreased mucus viscoelasticity, and shearing at the air mucus interface that occurs with the transient change in air flow with each high-frequency cycle.^{6-9,16-20}

Previous studies have demonstrated the efficacy of HFPV in the treatment of closed head injury, acute respiratory diseases caused by burns and smoke inhalation, and obesity in patients after lung surgery and during chest physiotherapy in cystic fibrosis patients.²² However, those previous trials were limited by small numbers of patients and outdated ventilation strategies for the control group, and this approach remains an unproven therapy for adults with ARDS.

In our case report, we used trials of HFPV in an attempt to rescue a patient who was experiencing increasing complications with ECMO therapy for respiratory failure and septic shock. This alternative mode of ventilation resulted in an increased Pao₂/Fio₂ ratio immediately after the first daily session that persisted after treatment was stopped.

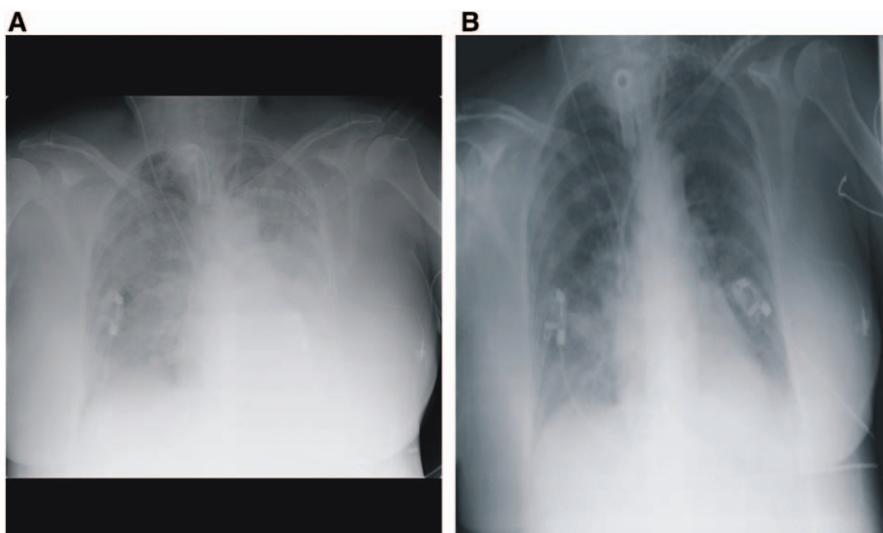


Figure 6. Computed tomography (CT) scan after high-frequency percussive ventilation (HFPV) treatment. For CT scan before HFPV, see Figure 3.

It is unclear why HFPV appeared to facilitate separation from ECMO in our patient, but current literature suggests 3 potential mechanisms: (1) improved lung recruitment, leading to increased respiratory system compliance and improved ventilation/perfusion relationships²³; (2) increased lung secretion clearance, which was prolonged after the end of treatment²⁴; and (3) better distribution of TV among different lung compartments.²⁵

According to the 2013 OSCAR and OSCILLATE (High frequency Oscillation in ARDS, and The Oscillation for ARDS Treated Early Trial) trials, HFPV did not reduce 30-day mortality in patients undergoing mechanical ventilation for ARDS. However, these patients were not supported on ECMO during

Figure 7. A and B, Chest radiography before and after high-frequency percussive ventilation treatment.



their course. Whether HFPV may facilitate lung function and shorten the course of ECMO therapy for acute respiratory failure remains unknown. HFPV could be a promising strategy for potentially improving lung recruitment and secretion clearance during ECMO separation in the critically ill patient.^{13,14} ■■

REFERENCES

1. Fitzgerald JC, Topjian AA, McInnes AD, Mattei P, McCloskey JJ, Friess SH, Kilbaugh TJ. Bi-caval dual lumen venovenous extracorporeal membrane oxygenation and high-frequency percussive ventilatory support for postintubation tracheal injury and acute respiratory distress syndrome. *J Pediatr Surg* 2011;46:e11–5
2. Raouf S, Goulet K, Esan A, Hess DR, Sessler CN. Severe hypoxemic respiratory failure: part 2—nonventilatory strategies. *Chest* 2010;137:1437–48
3. Javidfar J, Brodie D, Wang D, Ibrahimiyeh AN, Yang J, Zwischenberger JB, Sonett J, Bacchetta M. Use of bicaval dual-lumen catheter for adult venovenous extracorporeal membrane oxygenation. *Ann Thorac Surg* 2011;91:1763–8
4. Carman B, Cahill T, Warden G, McCall J. A prospective, randomized comparison of the volume diffusive respirator vs conventional ventilation for ventilation of burned children. 2001 ABA paper. *J Burn Care Rehabil* 2002;23:444–8
5. Rodeberg DA, Maschinot NE, Housinger TA, Warden GD. Decreased pulmonary barotrauma with the use of volumetric diffusive respiration in pediatric patients with burns: the 1992 Moyer Award. *J Burn Care Rehabil* 1992;13:506–11
6. Salim A, Martin M. High-frequency percussive ventilation. *Crit Care Med* 2005;33:S241–5
7. Kallet RH. Adjunct therapies during mechanical ventilation: airway clearance techniques, therapeutic aerosols, and gases. *Respir Care* 2013;58:1053–73
8. Cioffi WG, Graves TA, McManus WF, Pruitt BA Jr. High-frequency percussive ventilation in patients with inhalation injury. *J Trauma* 1989;29:350–4
9. Davis K, Hurst JM, Branson RD. High frequency percussive ventilation. *Prob Respir Care* 1989;2:39–47
10. The Acute Respiratory Distress Syndrome Network. Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. *N Engl J Med* 2000;342:1301–8
11. Brower RG, Lanken PN, MacIntyre N, Matthay MA, Morris A, Ancukiewicz M, Schoenfeld D, Thompson BT; National Heart, Lung, and Blood Institute ARDS Clinical Trials Network. Higher versus lower positive end-expiratory pressures in patients with the acute respiratory distress syndrome. *N Engl J Med* 2004;351:327–36
12. Briel M, Meade M, Mercat A, Brower RG, Talmor D, Walter SD, Slutsky AS, Pullenayegum E, Zhou Q, Cook D, Brochard L, Richard JC, Lamontagne F, Bhatnagar N, Stewart TE, Guyatt G. Higher vs lower positive end-expiratory pressure in patients with acute lung injury and acute respiratory distress syndrome: systematic review and meta-analysis. *JAMA* 2010;303:865–73
13. Ferguson ND, Cook DJ, Guyatt GH, Mehta S, Hand L, Austin P, Zhou Q, Matte A, Walter SD, Lamontagne F, Granton JT, Arabi YM, Arroliga AC, Stewart TE, Slutsky AS, Meade MO; OSCILLATE Trial Investigators; Canadian Critical Care Trials Group. High-frequency oscillation in early acute respiratory distress syndrome. *N Engl J Med* 2013;368:795–805
14. Young D, Lamb SE, Shah S, MacKenzie I, Tunnicliffe W, Lall R, Rowan K, Cuthbertson BH; OSCAR Study Group. High-frequency oscillation for acute respiratory distress syndrome. *N Engl J Med* 2013;368:806–13
15. Forti A, Salandin V, Zanatta P, Persi B, Sorbara C. Haemodynamics and oxygenation improvement induced by high frequency percussive ventilation in a patient with hypoxia following cardiac surgery: a case report. *J Med Case Rep* 2010;4:339
16. Cheng R, Hachamovitch R, Kittleson M, Ptel J, Arabia F, Moriguchi J, Esmailian F, Azarbal B. Complications of extracorporeal membrane oxygenation for treatment of cardiogenic shock and cardiac arrest: a meta-analysis of 1866 adult patients. *Ann Thorac Surg* 2014;97:610–6
17. Kagawa E, Inoue I, Kawagoe T, Ishihara M, Shimatani Y, Kurisu S, Nakama Y, Dai K, Takayuki O, Ikenaga H, Morimoto Y, Ejiri K, Oda N. Assessment of outcomes and differences between in- and out-of-hospital cardiac arrest patients treated with cardiopulmonary resuscitation using extracorporeal life support. *Resuscitation* 2010;81:968–73
18. Unosawa S, Sezai A, Hata M, Nakata K, Yoshitake I, Wakui S, Kimura H, Takahashi K, Hata H, Shiono M. Long-term outcomes of patients undergoing extracorporeal membrane oxygenation for refractory postcardiomy cardiogenic shock. *Surg Today* 2013;43:264–70
19. Dimassi S, Vargas F, Lyazidi A, Roche-Campo F, Dellamonica J, Brochard L. Intrapulmonary percussive ventilation superimposed on spontaneous breathing: a physiological study in patients at risk for extubation failure. *Intensive Care Med* 2011;37:1269–76
20. Gothern M, Buchwald D, Schlebels A, Strauch JT, Schildhauer TA, Swol J. Use of extracorporeal membrane oxygenation in combination with high-frequency oscillatory ventilation in post-traumatic ARDS. *Acta Anaesthesiol Scand* 2013;57:391–4
21. Dmello D, Nayak RP, Matuschak GM. High-frequency percussive ventilation for airway clearance in cystic fibrosis: a brief report. *Lung* 2010;188:511–3

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22. Lucangelo U, Zin WA, Fontanesi L, Antonaglia V, Peratoner A, Ferluga M, Marras E, Borelli M, Ciccolini M, Berlot G. Early short-term application of high-frequency percussive ventilation improves gas exchange in hypoxemic patients. *Respiration* 2012;84:369–76
 23. Allardet-Servent J, Bregeon F, Delpierre S, Steinberg JG, Payan MJ, Ravailhe S, Papazian L. High-frequency percussive ventilation attenuates lung injury in a rabbit model of gastric juice aspiration. *Intensive Care Med* 2008;34:91–100
 24. Lucangelo U, Antonaglia V, Zin WA, Confalonieri M, Borelli M, Columban M, Cassio S, Batticci I, Ferluga M, Cortale M, Berlot G. High-frequency percussive ventilation improves perioperatively clinical evolution in pulmonary resection. *Crit Care Med* 2009;37:1663–9
 25. Lucangelo U, Accardo A, Bernardi A, Ferluga M, Borelli M, Antonaglia V, Riscica F, Zin WA. Gas distribution in a two-compartment model ventilated in high-frequency percussive and pressure-controlled modes. *Intensive Care Med* 2010;36:2125–31