A Guide to Positive Pressure Ventilation in the Cardiac Intensive Care Unit: Council Perspective for the ACC Critical Care Cardiology Working Group

ONLINE SUPPLEMENT

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Online Figures: 1-5
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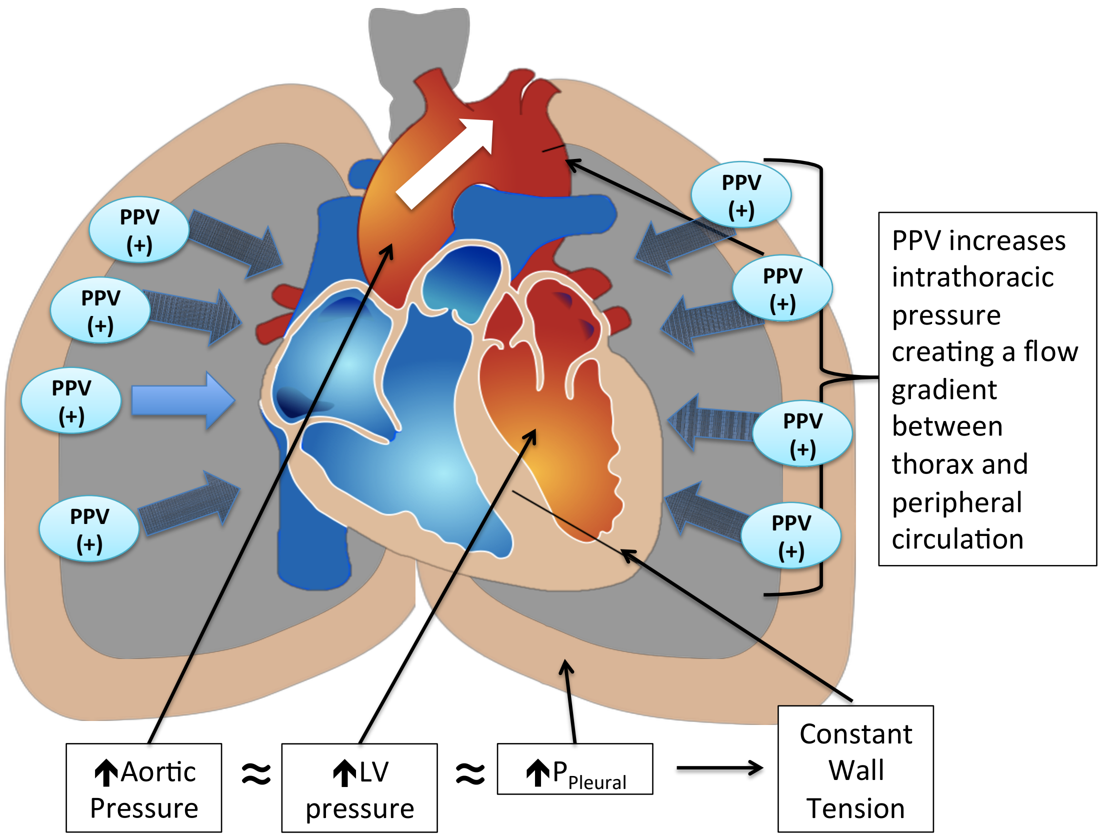
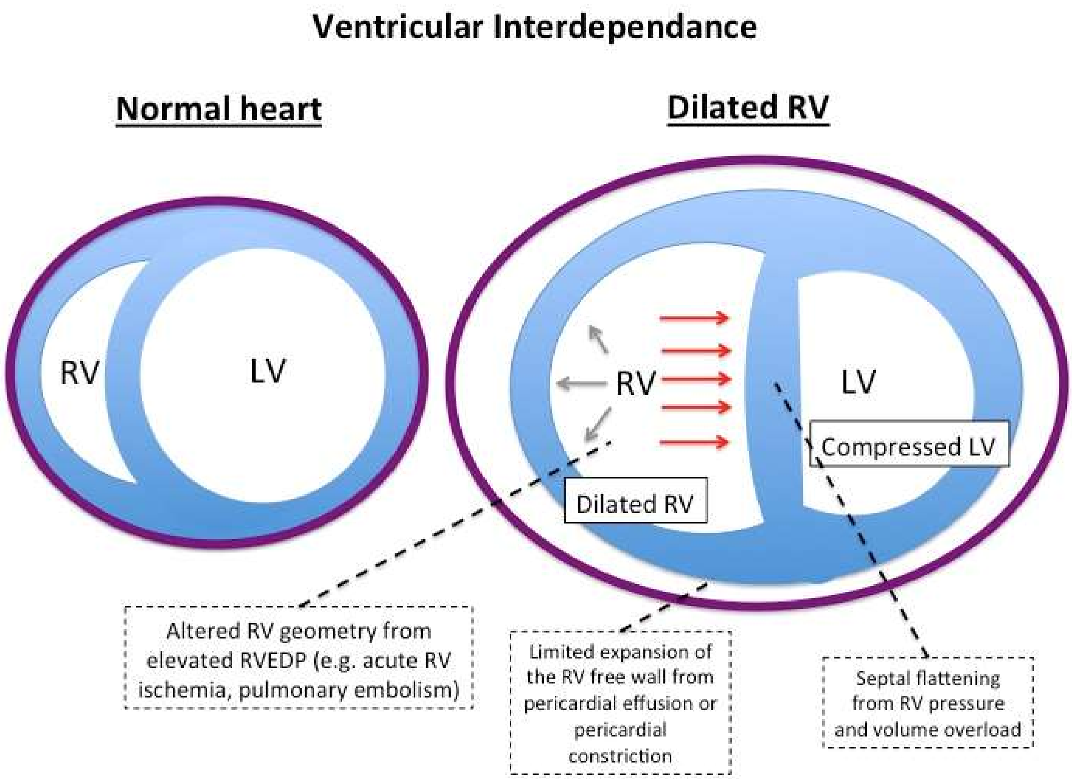
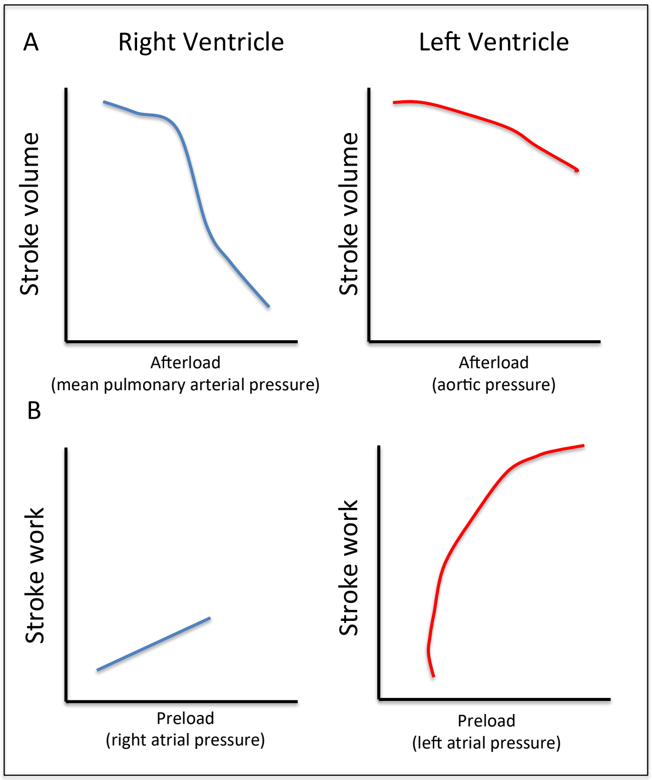
Online Figure 1. Intrathoracic pressure during positive pressure ventilation (PPV). As pleural pressure ($P_{pleural}$) increases, left ventricular (LV) pressure and aortic pressure also increase, maintaining wall tension constant. PPV also generates a pressure and flow gradient between thorax and peripheral organs (intra-aortic balloon pump-like effect).



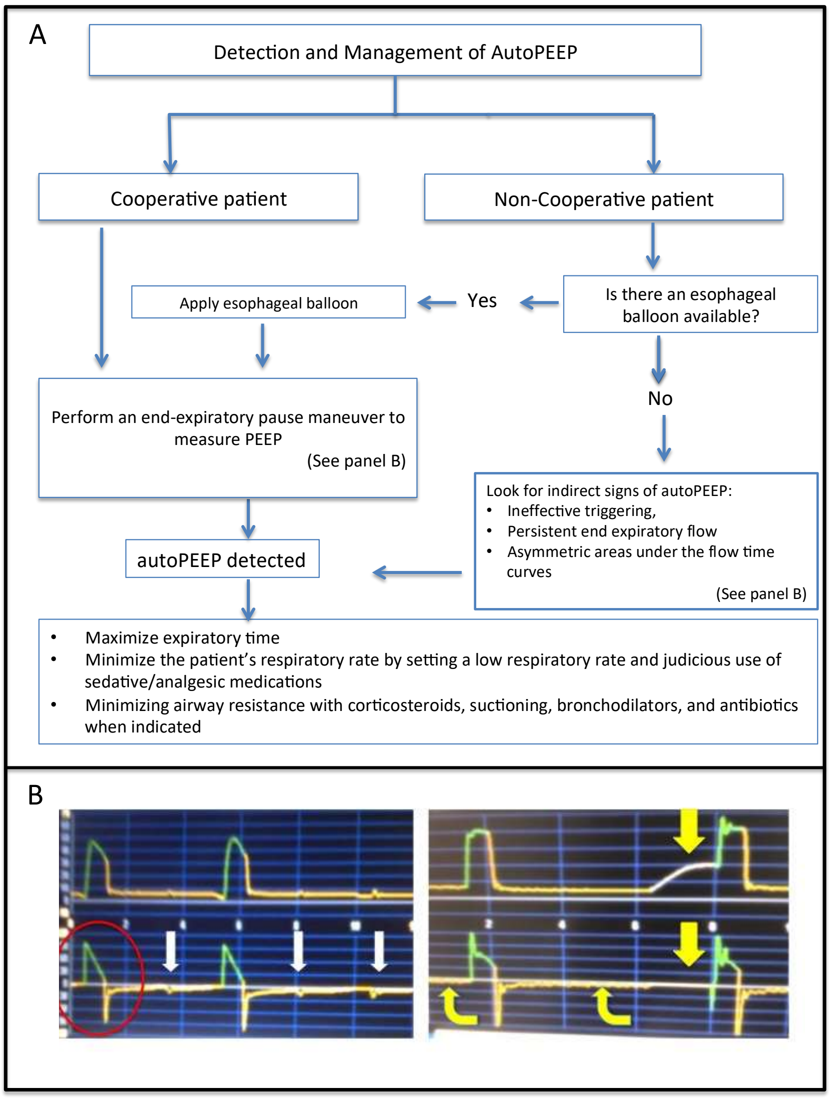
Online Figure 2. Ventricular interdependence in right ventricular (RV) failure. Dilatation and/or pressure overload of the RV, lead to changes in RV geometry that may shift the interventricular septum toward the left compressing (red arrows) the left ventricle (LV) and potentially compromising stroke volume and consequently cardiac output. Similarly, in cases where the RV free wall cannot expand (grey arrows), such as in pericardial tamponade or constriction, the septum may be displaced to the left. Adapted from Haddad (17).



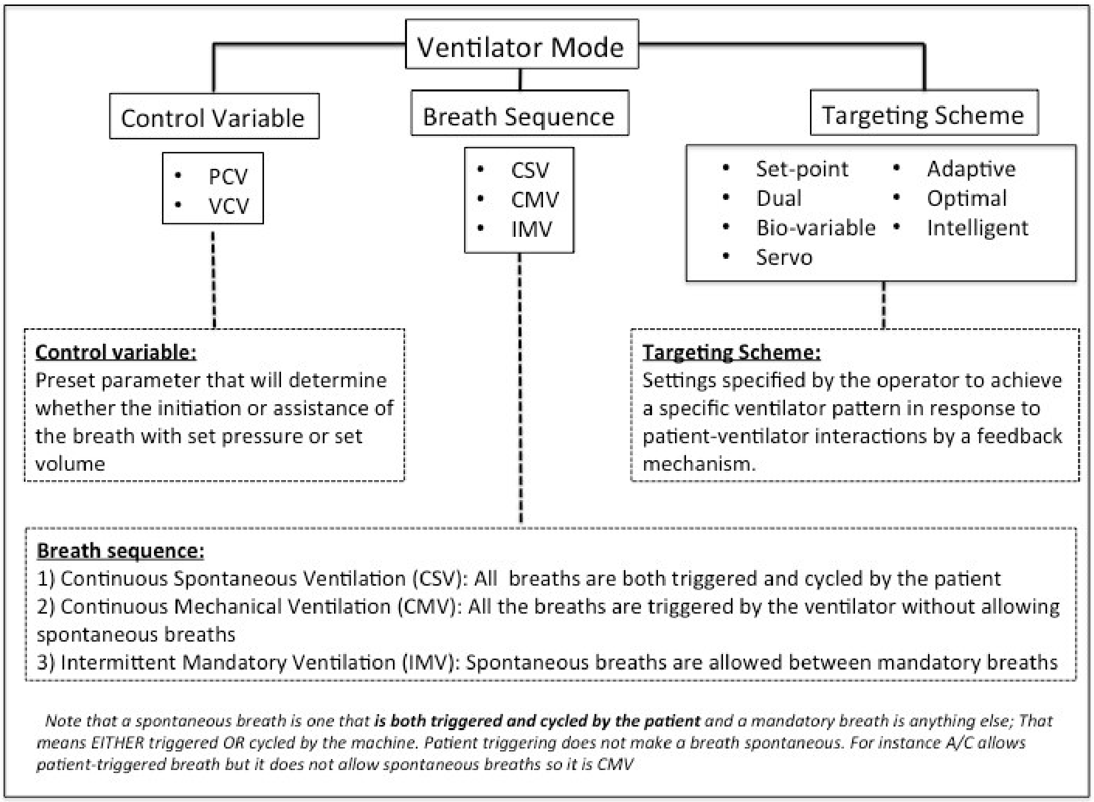
Online Figure 3. LV and RV adaptation to pressure and volume increase. A) As mean pulmonary pressure increases, right ventricular (RV) stroke volume decreases steeply. In contrast, the left ventricle (LV) adapts relatively well to increased afterload such that LV stroke volume does not decrease as much as RV stroke volume. B) The RV but not the LV adapts well to volume overload. The stroke work of the LV increases dramatically when preload (left atrial pressure) is increased, which is not the case for the RV. Adapted from MacNee W. Pathophysiology of cor pulmonale in chronic obstructive pulmonary disease. Part One. Am J Respir Crit Care Med 1994;150:833-52.



Online Figure 4. Approach to detect and manage auto-PEEP. A) Algorithm that may be applied at the bedside. B) Examples of pressure-time and flow-time curves suggesting auto-PEEP. Left, Pressure-time (top) and the flow-time curves (bottom) for a volume control breath. White arrows indicate evidence of ineffective triggering efforts, the most common cause of which is auto-PEEP. Notice the asymmetry in the area-under-the-curve for inspiratory vs. expiratory portions of the flow curve (red circle) which can be a sign of obstructive airway disease. Right, Pressure-time and the flow-time curves for a pressure control breath. The set PEEP is 5 cm H_2O. The clinician performed an end-expiratory breath hold (block yellow arrow) to measure auto-PEEP which is ~20 cm H_2O (top block yellow arrow). In addition, there is subtle persistence of end expiratory flow (curved yellow arrows) which suggests that the alveolar pressure is still higher than the set PEEP. Notice again the asymmetry in the area-under-the-curve for inspiratory vs. expiratory portions of the flow curve.



Online Figure 5. Definition of a ventilator mode by taxonomy. The control variable and breath sequence allow a simple classification of the ventilator mode. The targeting scheme refers to a pre-set algorithm in the ventilator that will respond to patient-ventilator interaction via feedback mechanisms. These settings are explained in detail in Chatburn RL et al. Respir Care 2014; 59:1747–63. PCV = pressure controlled ventilation; VCV = volume controlled ventilation



Online Table 1. Advantages and Disadvantages of Full-face/Oronasal Mask Compared with Nasal Mask for Non-Invasive Positive Pressure Ventilation

Advantages	***Disadvantages***
Minimizes air leak through the mouth	Less comfortable
Well-studied in respiratory failure	Higher risk of aspiration with emesis
Improved tidal volume and minute ventilation	Increased amounts of dead space
	More commonly causes nasal abrasions
	Limits speech and eating

Based on information from Navalesi, P, et al. Physiologic evaluation of noninvasive mechanical ventilation delivered with three types of masks in patients with chronic hypercapnic respiratory failure. Crit Care Med. 2000;28:1785-1890.

Online Table 2. Factors associated with failure of non-invasive positive pressure ventilation

- Worsening mental status
- Worsening hypoxia
- Hemodynamic or electrical instability
- Active vomiting
- Inability to protect the airway
- Increased work of breathing
- Myocardial infarction Killip class IV
- LV ejection fraction <30%
- Markedly elevated brain natriuretic peptide
- Positive fluid balance ≥400 mL in the preceding 24 hours

Online Table 3. Four elements to be set during IM-PPV related to respiratory phases.

	Definition	Options	Comments
Trigger	Event that will initiate a breath after reaching a determined threshold. The ventilator delivers a spontaneously triggered breath in coordination with patient's inspiratory effort when that effort exceeds the sensitivity threshold.	Flow-triggered: Patient's effort creates a change in flow to meet the threshold. Used in VC, PC, PS Pressure-triggered: Pressure change from PEEP generated by the patient meets the threshold. Used in VC, PC, PS Time-based: Minimum respiratory rate per minute Used in VC and PC	An overly sensitive trigger threshold can cause auto-triggering due to artifacts (e.g. air-leak, secretions), but an overly insensitive trigger can cause patient discomfort, agitation and increased work-of-breathing.
Cycling	Event that finishes the inspiratory phase of a breath. This takes place when the cycle variable reaches a pre-set value.	Volume is used in VC. Time is used in PC. Flow is used in PS. Pressure cycling is also used, but mostly for alarm settings.	During volume cycling, the volume that passes through the ventilator's output control valve is never exactly equal to the volume delivered due to the compressed volume in the circuit. Some ventilators compensate for the compressed gas in the TV coming out of the circuit.
Inspiratory control variable	Variable that tells the ventilator the amount of volume or pressure to deliver in each breath	Volume or pressure	Another volume-targeted ventilation (VTV), which is a dual-control mode with a set target TV, allows the ventilator to automatically adjust the pressure level to achieve the targeted TV (e.g. "VC+", or "autoflow").
Expiratory phase	Exhalation period where PEEP is applied	Duration can be adjusted according to I:E ratio, inspiratory flow velocity, respiratory rate and cycling variables. PEEP is selected at the operator's discretion	The clinician needs to be aware of the risk of auto-PEEP and to allow for adequate exhalation time or to adjust flow curves and inspiratory flow velocities to mitigate the development of auto-PEEP, especially in patients with obstructive airway disease.

Online Table 4. Overview of Pulmonary Mechanics for Selected Modes of Ventilation

	Relaxed Patient ($P_{muscle} = 0$)			Actively Inspiring Patient ($P_{muscle} < 0$)		
	PCV	**VCV**	**VTV**	**PCV**	**VCV**	**VTV**
Parameters Set by Clinician	P_{aw}, PEEP	F, V, PEEP	V, PEEP	P_{aw}, PEEP	F, V, PEEP	PEEP, V
Patient Characteristics	R, C	R, C	R, C	R, C, P_{muscle}	R, C, P_{muscle}	R, C, P_{muscle}
Variables that can change	F, V, auto-PEEP	P_{aw}, auto-PEEP	P_{aw}, F, auto-PEEP	F, V, auto-PEEP	P_{aw}, auto-PEEP	P_{aw}, F, V, auto-PEEP
Airway Pressure (P_{aw})	Set by the clinician	Determined by patient's R, C, and clinician-chosen F, V, PEEP. Will increase further if auto-PEEP.	Determined by patient's R, C, and clinician-chosen V, PEEP. Will increase further if auto-PEEP. Machine uses lowest P_{aw} to achieve the volume target. P_{aw} is constant during a given breath, but it will be adjusted from breath to breath as needed to achieve the volume target.	Set by the clinician Generally, P_{aw} will not change unless P_{muscle} outstrips the capacity of the ventilator to maintain the set pressure, in which case it may decrease.	Determined by patient's R, C, P_{muscle}, and clinician-chosen F, V, PEEP. Will increase further if auto-PEEP. May decrease with active inspiration (P_{muscle}).	Determined by patient's R, C, P_{muscle}, and clinician-chosen V & PEEP. Will increase further if auto-PEEP. Machine uses lowest P_{aw} to achieve the volume target. P_{aw} is constant during a given breath, but it will be adjusted from breath to breath to achieve volume target. This may lead to a decrease in P_{aw}.
Flow	Determined by patient's R, C, and clinician-chosen P_{aw}, PEEP. Will ↓ if auto-PEEP.	Set by the clinician	Determined by patient's R, C, and clinician-chosen V, PEEP, inspiratory time (IT).	Determined by patient's R, C, P_{muscle} and clinician-chosen P_{aw}, PEEP. Will ↓ if auto-PEEP. May increase with active inspiration (P_{muscle})	Set by the clinician	Determined by patient's R, C, P_{muscle}, and clinician-chosen V, PEEP, inspiratory time. May increase with active inspiration (P_{muscle})

TV	Determined by patient's R, C, and clinician-chosen P_{aw}, PEEP, IT. Will ↓ if auto-PEEP.	Set by the clinician	Set by the clinician.	Determined by patient's R, C, P_{muscle} and clinician-chosen P_{aw}, PEEP, IT. Will ↓ if auto-PEEP. May increase with active inspiration.	Set by the clinician	Set by the clinician. May increase with active inspiration.
$P_{plateau}$	Determined by resulting TV, auto-PEEP, patient's C, and clinician-chosen PEEP. Will be $\leq P_{aw}$	Determined by patient's C, and clinician-chosen V, PEEP. Will be $\leq P_{aw}$ Will increase if auto-PEEP.	Determined by patient's C, and clinician-chosen V, PEEP. Will be $\leq P_{aw}$ Will increase if auto-PEEP.	Determined by resulting TV, $PEEP_T$ & patient's C. May be $\leq$ or $\geq P_{aw}$ P_{muscle} may increase TV. If so $P_{plateau}$ will be higher than in the relaxed state.	Determined by patient's C, and clinician-chosen V, PEEP. May be $\leq$ or $\geq P_{aw}$ Will increase if auto-PEEP. P_{muscle} will not affect C, V or PEEP. If so $P_{plateau}$ will not change compared to the relaxed state.	Determined by resulting TV, patient's C, and clinician-chosen PEEP. May be $\leq$ or $\geq P_{aw}$ Will increase if auto-PEEP. P_{muscle} may increase TV. If so $P_{plateau}$ will be higher than in the relaxed state.

Equation of Motion: $P_{aw} - P_{muscle} = F*R + V / C + PEEP + auto\text{-}PEEP$