From Positive Airway Pressure to Extra-thoracic Expansion: Reconsidering Ventilation Strategy in Bronchopulmonary Dysplasia Hospital to Home

Physiologic Ventilation with Negative Pressure Support for Lung Recovery, Earlier NICU Discharge, and Seamless Transition to Home

Abstract

Bronchopulmonary dysplasia (BPD) and other forms of neonatal respiratory insufficiency remain among the most costly and clinically challenging conditions managed in neonatal intensive care units (NICUs). Advances in surfactant therapy, antenatal steroids, and gentle ventilation strategies have improved survival of extremely premature infants; however, long-term pulmonary morbidity remains common.

A growing body of physiologic and clinical evidence suggests that **negative pressure ventilation (NPV)** may offer a complementary strategy to traditional positive pressure ventilation for supporting lung recovery in fragile neonatal lungs. By generating airflow through **extrathoracic pressure changes that mimic normal diaphragmatic breathing**, NPV may reduce some of the lung injury mechanisms associated with sustained positive pressure ventilation.

Beyond its physiologic advantages, NPV offers a unique opportunity to establish a **continuous respiratory support pathway from hospital to home**. When incorporated into neonatal respiratory care strategies, NPV may:

- Support lung recruitment and recovery during NICU care
- Enable earlier transition off invasive ventilation and potentially reduce length of stay
- Provide a **non-invasive bridge to long-term home respiratory support**

This continuum-of-care model aligns with modern neonatal priorities: **lung protection, family-centered care, and efficient use of healthcare resources.**

Background: Respiratory failure in neonates and children is commonly managed with positive pressure ventilation, which can be life-saving but is also associated with ventilator-induced lung injury and disruption of physiologic breathing mechanics. These effects are particularly concerning in populations with fragile lungs, including premature infants and patients with evolving bronchopulmonary dysplasia. Negative pressure ventilation offers an alternative method of generating transpulmonary pressure that more closely replicates normal breathing mechanics and may reduce some of these physiologic burdens. This continuum-of-care model aligns with modern neonatal priorities: **lung protection, family-centered care, and efficient use of healthcare resources.**

Physiologic Rationale: Negative pressure ventilation reproduces the mechanics of normal inspiration by generating subatmospheric pressure around the thorax, thereby creating transpulmonary pressure gradients without direct airway pressurization. This approach may allow lung expansion while reducing alveolar overdistension and preserving venous return and cardiopulmonary interaction.

Evidence Overview: Historical and contemporary experience with negative pressure ventilation has demonstrated effectiveness in a variety of clinical settings, including neuromuscular respiratory failure, obstructive lung disease, and selected pediatric respiratory disorders. Modern biphasic cuirass systems have renewed interest in this physiologic modality by enabling noninvasive ventilation, secretion clearance, and lung recruitment strategies.

Clinical Implications: Integration of negative pressure ventilation into modern respiratory care pathways may provide an adjunctive strategy for supporting vulnerable lungs, facilitating lung recovery, and reducing exposure to high positive airway pressures.

Conclusions: Negative pressure ventilation represents a physiologically aligned approach to respiratory support that may complement existing ventilatory strategies and deserves renewed consideration in contemporary neonatal and pediatric respiratory care.

Key Question
Can respiratory support strategies that better replicate physiologic breathing mechanics improve long term outcomes in fragile neonatal lungs?

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1. The Clinical Challenge: Lung Injury and Prolonged NICU Dependence

Positive pressure ventilation remains the cornerstone of respiratory support for neonates and children with respiratory failure. However, the airway pressures required to maintain gas exchange may contribute to ventilator-induced lung injury and altered cardiopulmonary interactions, particularly in patients with fragile or developing lungs. Negative pressure ventilation generates transpulmonary pressure through thoracic expansion rather than airway pressurization, potentially offering a more physiologic approach to respiratory support.

Interest in this modality has re-emerged with the development of modern biphasic cuirass systems such as the Hayek RTX Biphasic Cuirass Ventilator, which allow noninvasive ventilation, lung recruitment, and secretion clearance while preserving spontaneous breathing mechanics.

Historical and contemporary clinical experience suggests that negative pressure ventilation may have valuable applications in neonatal respiratory support, neuromuscular respiratory insufficiency, and selected obstructive or restrictive lung disorders. Integration of physiologically aligned ventilation strategies into modern respiratory care pathways may provide opportunities to reduce exposure to high positive airway pressures while supporting lung recovery.

Renewed evaluation of negative pressure ventilation in contemporary clinical practice may therefore be warranted, particularly in patient populations vulnerable to ventilator-associated lung injury.

Premature infants with respiratory insufficiency frequently require prolonged respiratory support due to:

- Surfactant deficiency
- Immature chest wall mechanics
- Inflammation and ventilator-associated lung injury
- Atelectasis and impaired lung growth

Even with lung-protective positive pressure strategies, complications may include:

- Ventilator-induced lung injury
- Volutrauma and barotrauma
- Airway injury
- Increased risk of developing or worsening BPD

These factors often prolong respiratory support and delay safe discharge.

As NICUs increasingly emphasize **non-invasive and physiologic ventilation strategies**, interest has re-emerged in methods that support breathing while minimizing airway pressures.

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2. Physiologic Basis of Negative Pressure Ventilation

Negative pressure ventilation recreates the **normal mechanics of breathing**.

During spontaneous respiration:

1. The diaphragm contracts
2. Intrathoracic pressure becomes negative
3. Air flows naturally into the lungs

NPV recreates this process externally by applying **cyclic negative pressure around the thorax**, allowing the lungs to inflate in a manner similar to natural breathing.

Potential physiologic advantages include:

Reduced Transpulmonary Stress

Unlike positive pressure ventilation, which pushes air into the lungs through airway pressure, NPV expands the lungs by reducing surrounding thoracic pressure.

Improved Venous Return and Hemodynamics

Negative intrathoracic pressure can enhance venous return compared with positive pressure ventilation.

More Uniform Lung Inflation

NPV may promote recruitment of dependent lung regions that can remain under-ventilated during positive pressure ventilation.

Reduced Airway Trauma

Because airway pressures can remain low, NPV may reduce risk of airway injury and barotrauma.

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3. Supporting Lung Recovery in the NICU

Within the NICU, NPV may be used as part of a **lung-protective respiratory support strategy** in infants with evolving or established lung disease.

Potential roles include:

Non-Invasive Ventilatory Support

NPV can support tidal ventilation without the need for high airway pressures.

Lung Recruitment

Alternating negative and positive cuirass pressures may assist with gradual lung recruitment and improved functional residual capacity.

Airway Clearance

Oscillatory and cough-assist features can support secretion mobilization in infants with impaired airway clearance.

Support During Weaning

NPV may serve as an intermediate step when transitioning from mechanical ventilation to spontaneous breathing.

For infants recovering from respiratory failure, these mechanisms may allow for **progressive lung recovery while minimizing additional injury.**

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4. Facilitating Earlier Discharge from the NICU

Length of stay in the NICU is often prolonged by the need for ongoing respiratory support, even after other medical issues have stabilized.

A respiratory support approach that:

- avoids invasive airways
- supports spontaneous breathing
- can be safely continued outside the hospital

may allow clinicians to consider **earlier transition to home-based care** for selected patients.

Potential benefits include:

Reduced NICU Length of Stay

Infants who remain otherwise stable but require ongoing respiratory support may be discharged earlier if non-invasive support can be maintained safely at home.

Improved Family Integration

Earlier transition home supports family bonding and developmental environments.

Reduced Hospital Costs

NICU care represents one of the highest-cost areas in healthcare. Even modest reductions in length of stay can have significant economic impact.

Importantly, these benefits depend on **appropriate patient selection, caregiver training, and structured follow-up programs.**

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5. Seamless Transition to Home Respiratory Support

One of the most distinctive advantages of NPV technology is its ability to function in **both hospital and home environments**.

This allows for a **continuity of respiratory support strategy**.

In the NICU

NPV may be introduced during the recovery phase of respiratory illness.

During Discharge Planning

Caregivers can be trained on the same support system used in the hospital.

At Home

NPV can provide ongoing respiratory support during lung growth and recovery.

This continuity offers several advantages:

- Familiarity for caregivers
- Reduced equipment transitions
- Stable respiratory management strategies
- Reduced hospital readmission risk

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6. Long-Term Benefits for Infants with Chronic Lung Disease and Their Families

Infants with BPD often experience prolonged respiratory vulnerability even after discharge.

Ongoing support strategies that maintain physiologic breathing patterns may help:

- Reduce respiratory workload
- Support lung growth and remodeling
- Reduce frequency of hospital readmissions
- Improve sleep and feeding tolerance
- Language development advantages

Home-based NPV may therefore serve as a **bridge during the critical months of post-NICU lung development.**

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7. Health System and Economic Considerations

Healthcare systems increasingly prioritize strategies that:

- improve patient outcomes
- reduce ICU length of stay
- enable safe outpatient care

A hospital-to-home NPV pathway may contribute to these goals by:

Reducing ICU Resource Utilization

Earlier transition out of the NICU frees high-acuity beds.

Supporting Value-Based Care

Reducing complications and readmissions aligns with value-based reimbursement models.

Enhancing Care Continuity

Standardizing respiratory support across care environments improves clinical consistency.

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8. Implementation Considerations

Successful integration of NPV into a hospital-to-home care pathway requires:

Multidisciplinary Collaboration

Including neonatology, pulmonology, respiratory therapy, nursing, and home care teams.

Patient Selection

Identifying infants who may benefit from physiologic ventilation strategies.

Caregiver Training

Structured education programs for families prior to discharge.

Home Monitoring

Appropriate follow-up and respiratory support monitoring.

When implemented within structured programs, NPV may become part of a **comprehensive respiratory management strategy** rather than a stand-alone technology.

The central question posed in this analysis is whether respiratory support strategies that more closely replicate physiologic breathing mechanics can improve lung recovery and long-term outcomes in infants with evolving Bronchopulmonary Dysplasia. Current physiologic understanding, historical clinical experience with negative pressure ventilation, and emerging capabilities of modern biphasic cuirass systems collectively suggest that the answer is **likely yes—particularly when such strategies are applied early and sustained across the continuum of care**. By generating transpulmonary pressure through thoracic expansion rather than positive airway pressurization, negative pressure ventilation offers a mechanism for supporting gas exchange while potentially reducing cumulative ventilator-associated lung stress. When integrated across NICU stabilization, step-down respiratory support, and carefully supervised home care using contemporary systems such as the Hayek RTX Biphasic Cuirass Ventilator, physiologic ventilation may provide a coherent pathway for protecting vulnerable lungs while allowing time for continued pulmonary growth and recovery.

Conclusion

Advances in neonatal care have dramatically improved survival among extremely premature infants. The next frontier in neonatal respiratory management is reducing long-term lung injury while supporting healthy lung development. The persistent burden of Bronchopulmonary Dysplasia reflects the limitations of relying exclusively on positive airway-pressurizing ventilation strategies in these vulnerable patients. Negative pressure ventilation restores the fundamental mechanics of physiologic breathing while supporting safe and effective lung recruitment and secretion clearance.

Negative pressure ventilation represents a physiologically grounded approach that can help achieve these goals.

When integrated into a **hospital-to-home continuum of care**, NPV has the potential to:

- Support lung recovery in the NICU
- Facilitate earlier and safer discharge
- Provide ongoing respiratory support during the critical period of post-discharge lung growth
- Bring about improved quality of life for infant and their families

By aligning physiologic respiratory support with modern care delivery models, NPV may help advance the next generation of neonatal respiratory care strategies.

Appendix A

Clinical Evidence Supporting Physiologic Ventilation and Negative Pressure Approaches

1. Ventilator-Induced Lung Injury in Premature Infants

Mechanical ventilation is lifesaving but is also a recognized contributor to lung injury in premature infants. The immature lung is particularly susceptible to:

- Barotrauma
- Volutrauma
- Atelectrauma
- Oxygen toxicity

Exposure to **higher airway pressures and prolonged mechanical ventilation** has been associated with increased risk of complications such as pneumothorax and bronchopulmonary dysplasia (BPD).

Because of this risk, modern neonatal care increasingly emphasizes:

- early non-invasive ventilation
- minimizing ventilator days
- lung-protective strategies.

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2. Evidence Supporting Non-Invasive Ventilation

Reducing exposure to invasive ventilation has been shown to improve outcomes in preterm infants.

A systematic review of **24 randomized trials of non-invasive ventilation in premature infants with respiratory distress syndrome** found that non-invasive strategies can reduce:

- reintubation
- duration of mechanical ventilation
- incidence of BPD compared with traditional approaches.

Reducing ventilator days is widely considered a key strategy for preventing chronic lung disease of prematurity.

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3. Clinical Experience with Negative Pressure Ventilation

While positive pressure ventilation has dominated neonatal respiratory care for decades, negative pressure ventilation has periodically demonstrated clinical benefit.

A clinical case series of critically ill infants using **chest cuirass negative pressure ventilation** reported:

- improvement in respiratory status
- reduced need for more invasive ventilation
- avoidance of complications associated with invasive ventilation.

These observations suggest that **negative pressure ventilation can serve as a viable non-invasive respiratory support modality** in selected pediatric and neonatal patients.

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4. Physiologic Rationale

Negative pressure ventilation restores the **normal mechanics of breathing**:

- diaphragm contraction creates negative intrathoracic pressure
- lungs expand naturally and mor homogenously
- airflow follows less lung stressful physiologic pressure gradients.

In contrast, positive pressure ventilation inflates the lungs by forcing air into the airway, which may concentrate ventilation in already-open lung units and increase mechanical stress on fragile lung tissue.

This difference is the core rationale behind **physiologic ventilation strategies**.

Positive Pressure vs Negative Pressure Ventilation

Comparison of physiologic mechanisms relevant to BCV/NPV

Mechanism	Positive Pressure Ventilation (PPV)	Negative Pressure Ventilation (NPV / BCV)
Air Entry Mechanism	Air pushed into lungs via airway pressure	Thoracic expansion creates negative intrathoracic pressure drawing air in
Alveolar Stress	Higher due to airway pressurization	Lower due to physiologic pressure gradient
Venous Return	May decrease due to increased intrathoracic pressure	Improves due to negative intrathoracic pressure

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Appendix B

Health Economics and NICU Resource Utilization

NICU care represents one of the most resource-intensive areas of modern healthcare.

Typical NICU costs in the United States:

Category	Approximate Cost
Average NICU day	$3,000–$5,000
Extremely preterm infant hospitalization	$250,000–$1,000,000
BPD management in first year	$50,000–$200,000

Respiratory support is one of the **primary drivers of NICU length of stay**.

Potential System-Level Benefits of an NPV Continuum Strategy

1. Reduced Mechanical Ventilation Duration

If physiologic ventilation strategies reduce ventilator days, this may:

- decrease ventilator-associated complications
- shorten recovery time
- decreased readmissions

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2. Earlier NICU Discharge

Many premature infants remain hospitalized **solely because they still require respiratory support**.

If that support can safely continue at home:

- NICU length of stay may be reduced
- step-down units may be bypassed or stay shortened

Even a **5–10 day reduction in NICU stay** could yield:

NICU Reduction	Estimated Savings per Patient
5 days	$15,000–$25,000
10 days	$30,000–$50,000

Across a moderate-sized NICU managing **40–60 BPD infants annually**, potential system savings may exceed:

$1–2 million per year

while maintaining high-quality respiratory care.

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3. Reduced Readmissions

Respiratory instability is a major cause of readmission for infants with BPD.

Providing **stable home respiratory support** during early lung development may:

- reduce respiratory exacerbations
- decrease emergency department visits
- reduce hospital readmissions
- enhance linguistic development

Appendix C

Hospital-to-Home Respiratory Care Pathway

The most compelling concept for hospital administrators is **continuity of respiratory strategy**.

Below is the conceptual model.

Ventilation goal: Always support an open lung without use of damaging positive pressures

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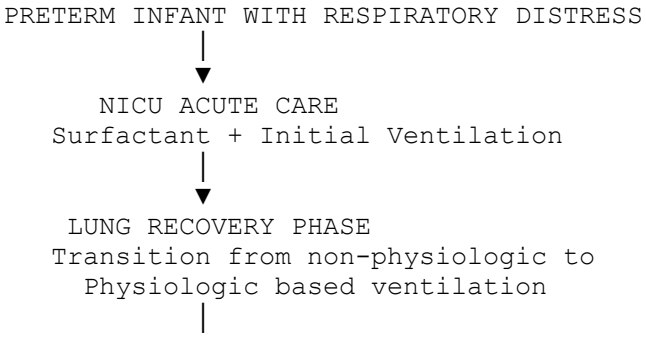
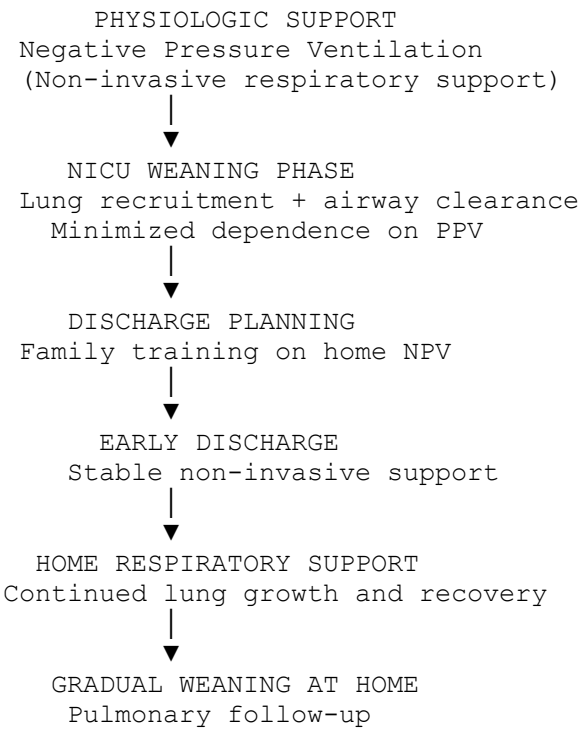
The Hospital-to-Home Physiologic Ventilation Pathway





Strategic Advantages of the Continuum Model

For Clinicians

- Lung-protective respiratory strategy
- Reduced ventilator injury risk
- Reduced cardiovascular compromise
- Decreased sedation requirements
- Improved enteral nutrition
- Supports spontaneous breathing.

For Families

- Earlier bonding at home
- Reduced NICU separation
- Familiar respiratory support system.

For Hospitals

- Reduced NICU bed utilization
- Lower total cost of care
- Improved resource allocation.

Key Takeaway

The most powerful value proposition is **not simply a ventilator modality**, but a **care model**:
Hospital → Recovery → Home

With the availability of modern biphasic cuirass ventilation systems such as the Hayek RTX Biphasic Cuirass Ventilator, clinicians now have the opportunity to incorporate physiologic ventilation into a broader continuum of care—from the NICU to the home environment—potentially reducing cumulative ventilator injury while supporting lung recovery during the critical period of postnatal development.

A physiologic ventilation strategy that begins in the NICU and continues seamlessly into the home environment may allow neonatal care to evolve from **prolonged ICU dependence to earlier supported recovery in the family setting.**

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