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인공호흡기 이탈을 위한 원인 기반 접근법: 자발호흡 시도를 넘어

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Beyond Spontaneous Breathing Trials: An Etiology-Based Framework for Ventilator Weaning Across Critical Care and Rehabilitation Medicine

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Abstract

Liberation from mechanical ventilation has long been approached as a protocolized problem in the intensive care unit (ICU), with spontaneous breathing trial (SBT)-based frameworks refined over decades by pulmonology and critical care. This approach succeeds in patients with parenchymal lung disease, but a substantial subset of ventilator-dependent patients fails repeated weaning attempts because of pathophysiologic processes that ICU-based protocols are not designed to address. This narrative review proposes a complementary, etiology-based framework that classifies ventilator-dependent patients into four categories: (1) pulmonary, in which gas exchange and lung mechanics dominate and SBT protocols apply; (2) muscle, in which respiratory muscle weakness — including ICU-acquired weakness, ventilator-induced diaphragm dysfunction, and neuromuscular disease — necessitates muscle support, with non-invasive ventilation enabling extubation without tracheostomy in selected patients; (3) brain, in which central respiratory drive impairment requires recognition of demand-modifying factors and acceptance of a longer recovery timeline given brainstem plasticity; and (4) aspiration, which overlaps with the other categories but warrants separate consideration because airway protection failure — not respiratory dysfunction — drives ventilator dependence. For three of these four etiologies, weaning need not be completed within the ICU and may proceed in post-acute settings where rehabilitation medicine provides structured intervention. The author argues that weaning failure in many patients reflects a diagnostic mismatch rather than protocol inadequacy, and that recognition of this distinction enables more accurate venue selection and earlier referral. The framework is offered not as a replacement for established protocols, but as a complementary lens for patients in whom standard approaches stall.

Key Words

Mechanical ventilation, Weaning, Non-invasive ventilation, Tracheostomy

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Introduction

Liberation from mechanical ventilation has been a central concern of critical care medicine for decades. Pulmonology and critical care have developed and refined spontaneous breathing trial (SBT)-based weaning protocols, and these approaches yield reliable outcomes in patients whose ventilator dependence stems from primary lung pathology — recovering ARDS, severe pneumonia, COPD exacerbation, and post-thoracic surgery patients [1,2]. Major guidelines, including those from the American Thoracic Society / American College of Chest Physicians, recommend SBT-based protocols as standard practice, and the evidence that this framework reduces weaning failure and shortens ICU length of stay is well established [3].

However, not every ventilator-dependent patient encountered in clinical practice is well served by this framework. There is a recognizable subgroup of patients who fail repeated SBTs, in whom incremental adjustments to ventilator settings yield no progress, and who are eventually labeled "unweanable" and consigned to prolonged mechanical ventilation. Some of these patients have lung parenchyma damaged beyond recovery; others, however, do not have a primary lung problem at all, but rather a different pathophysiologic axis driving their ventilator dependence. This may be respiratory muscle weakness, central respiratory drive impairment, or — in a category distinct from respiratory function itself — failure of airway protection.

The fact that standard SBT protocols offer limited benefit in these patients is not a failure of protocol design. SBTs are an integrated bedside stress test of spontaneous breathing capacity — they reliably reveal whether the patient can sustain spontaneous breathing under reduced support, but they do not by themselves identify the dominant cause when sustained breathing cannot be achieved. When ventilator dependence is not primarily a pulmonary problem, additional evaluation along axes other than the lung is required to identify the actual limiting factor, and the interventions that would address it never reach the patient otherwise. This is not a protocol failure, but a diagnostic mismatch. In this review, the term diagnostic mismatch denotes situations in which a standard diagnostic tool is applied to a clinical problem outside its intended diagnostic domain.

This narrative review proposes a complementary framework that classifies ventilator-dependent patients according to the dominant etiology of their ventilator dependence. The framework is not intended to replace standard weaning protocols, but to organize the clinical contributions of rehabilitation medicine in the territory where those protocols struggle. The classification consists of four categories: pulmonary, muscle, brain (i.e., central respiratory drive), and aspiration. The first three represent failures of respiration or of the systems that drive it; aspiration operates on a different axis — failure of airway protection — and constitutes a separate category. Each category demands its own evaluation tools, rehabilitation interventions, and weaning venue, and clinical decisions must be calibrated accordingly.

Main Text

1) The Standard Weaning Framework and Its Limits

Current weaning protocols were established through large-scale clinical trials and meta-analyses from the 1990s onward. The core structure is straightforward: a daily SBT is performed to assess whether the patient can sustain spontaneous breathing on minimal support for a defined period, and extubation proceeds if predefined criteria are met [1,3]. SBT evaluation indices focus on the lung's ventilatory and oxygenation capacity, work of breathing, and mechanical endurance — P/F ratio, arterial blood gas, compliance, plateau pressure, and the rapid shallow breathing index (RSBI, f/Vt). These tools are designed to quantify functional recovery of the lung itself.

This framework performs well when lung parenchyma or ventilatory mechanics are the primary problem. In patients recovering from ARDS, severe pneumonia, post-thoracic surgery courses, or atelectasis, SBT-based approaches shorten weaning time and reduce extubation failure rates [1,3]. ATS/ACCP clinical practice guidelines have synthesized this evidence into recommendations for protocolized weaning, and this framework remains central to ICU standard practice.

Nevertheless, the framework is not equally effective in every ventilator-dependent patient. The reason protocols do not work in some patients is not a flaw in protocol design. SBTs assess whether the patient can tolerate spontaneous breathing under reduced ventilatory support; they are not, however, designed to decompose the cause of failure when spontaneous breathing cannot be sustained. When a patient's ventilator dependence is driven by respiratory muscle weakness, central drive impairment, or aspiration risk, lower PEEP settings, shorter SBTs, and more refined titration cannot alter the underlying problem. What these patients need is not greater protocol precision, but identification of the actual cause of their ventilator dependence.

In sum, the standard weaning framework is an effective tool in patients with pulmonary problems, and there is no need to displace it within that domain. What must be recognized is that its applicable territory does not encompass all ventilator-dependent patients, and that patients outside that territory require a different evaluation axis and different intervention strategies. The next section presents an etiology-based framework intended for these patients.

2) An Etiology-Based Framework

The framework proposed here classifies ventilator-dependent patients into four categories according to the dominant etiology of their ventilator dependence. The classification turns on a single clinical question: why is this patient on the ventilator? In the author's clinical experience, the answer typically converges on one of four categories.

First, pulmonary. Cases in which oxygenation or ventilation is inadequate due to a problem with lung parenchyma or ventilatory mechanics themselves. ARDS, severe pneumonia, COPD exacerbation, and post-thoracic surgery atelectasis are representative. Although the primary pathology may be cardiac, heart failure and weaning-induced pulmonary edema are also grouped here because the immediate barrier to liberation is impaired cardiopulmonary gas exchange and increased respiratory load.

Second, muscle. Cases in which respiratory muscle weakness — primarily of the diaphragm — prevents the patient from generating sufficient work of breathing to substitute for the ventilator. ICU-acquired weakness (sepsis, prolonged immobilization, secondary weakness from prolonged MV) and ventilator-induced diaphragm dysfunction (VIDD) are common; patients with underlying neuromuscular disease such as Duchenne muscular dystrophy, ALS, or Guillain-Barré syndrome also fall in this category. High cervical cord injury requiring ventilatory support and phrenic nerve injury are likewise included.

Third, brain (central respiratory drive). Cases in which both the lung and respiratory muscles are relatively preserved, but the brainstem drive that propels respiration itself is impaired. Brainstem stroke (particularly involving the medulla or pons) and hypoxic brain injury (post-cardiac arrest, asphyxia) are representative. These patients have no abnormality in the organs directly involved in respiration — lung, muscle — but have impaired respiratory regulation due to dysfunction of the brain's respiratory control centers.

Fourth, aspiration. Aspiration is in fact not a domain entirely independent of the other three categories. Swallow function impairment commonly accompanies brain injury; in NMD patients with bulbar involvement, respiratory muscle weakness and swallow weakness progress in parallel; and pulmonary patients also face increased aspiration risk after prolonged intubation. In other words, aspiration frequently overlaps with the other categories.

The reason it merits separation as a distinct category here is that its clinical importance and its evaluation and intervention axes are sufficiently specific. Whereas the other three categories address failures of respiration or its driving systems, aspiration operates on a different axis — the patient's inability to protect their own airway. For these patients, the ventilator is often maintained not because of an oxygenation or ventilation problem, but for secretion management and aspiration prevention. Representative populations include brain injury (stroke, TBI, hypoxic brain injury), bulbar muscle weakness (ALS, MG, late-onset NMD), Parkinson's disease, and advanced age with sarcopenia.

These four categories are not mutually exclusive — patients commonly belong to two or more categories simultaneously. Brainstem injury patients, in particular, frequently exhibit both central drive impairment (brain category) and swallow function loss (aspiration category). Pulmonary-category patients with prolonged ICU stays often transition into the muscle category over time. Nevertheless, the starting point of clinical decision-making is identification of the dominant etiology, and the appropriate evaluation tools, intervention strategies, and weaning venue follow from that determination.

Before turning to category-specific strategies, one principle applies to all ventilator-dependent patients regardless of etiology. Every patient on a ventilator — by virtue of being on a ventilator — is undergoing deconditioning. They are sedated, immobilized, often nutritionally depleted, and time is passing.

In this review, the terms Floor and Ceiling denote two complementary layers of rehabilitation intervention that together structure the clinician’s approach to every ventilator-dependent patient. For this reason, every rehabilitation effort comprises two layers. The floor is universal: early mobilization, sedation minimization, nutritional optimization, and skin and joint care. These deconditioning-prevention strategies apply equally to patients in any category. The ceiling is cause-specific: it targets the dominant etiology, and the strategy and venue follow from that. The floor does not change; the ceiling shifts patient by patient. The next section focuses on the ceiling — the cause-specific strategies — for each category.

A summary of category-specific assessment tools, ceiling interventions, weaning endpoints, and recommended venues is provided in Table 1.

3) Category-Specific Clinical Strategies

(1) Pulmonary

The pulmonary category is the domain in which standard weaning protocols work best, and unlike the other sections of this review, there is little need to modify the existing framework. Evaluation is straightforward: P/F ratio, arterial blood gas, compliance and plateau pressure, imaging including lung ultrasound, and RSBI [1,3,4]. These tools have all been validated in this patient population and provide reliable information on weaning readiness.

Rehabilitation interventions consist of positioning (prone or semi-prone in the recovery phase of ARDS), airway clearance (positive expiratory pressure, active cycle of breathing technique), collaboration with recruitment maneuvers when needed, and graded mobilization under SpO_2 monitoring. Weaning strategy proceeds with progressive reduction of PEEP and pressure support, followed by extubation when criteria are met — this is the standard protocol unchanged [1,3,4]. ICU-based weaning is appropriate in this category, and transition to the general ward after extubation is relatively straightforward.

There is, however, a distinct subgroup within the pulmonary category that warrants separate attention: patients with chronic restrictive ventilatory failure, particularly post-tuberculosis destroyed lung — a condition encountered with notable frequency among older Korean patients. Decades after extensive parenchymal destruction from prior tuberculosis, these patients present with chronic hypercapnia and, at times, cor pulmonale, in a picture of chronic ventilatory failure. When such patients are admitted to the ICU and placed on a ventilator due to an

Table 1. Etiology-based Framework for Ventilator Weaning: Summary of Category-specific Assessment, Intervention, Weaning Endpoint, and Venue

Category	Representative etiologies	Dominant pathophysiology	Domain-specific assessment	Ceiling intervention (cause-specific)	Weaning endpoint	Recommended weaning venue
PULMONARY	Acute: ARDS, severe pneumonia, COPD exacerbation, post-thoracic surgery atelectasis, heart failure / weaning-induced pulmonary edema	Impaired gas exchange and lung mechanics	P/F ratio; ABG; compliance; plateau pressure; lung ultrasound; RSBI	Positioning (prone / semi-prone); airway clearance (PEP, ACBT); recruitment maneuvers; graded mobilization	Standard extubation after SBT pass	ICU
	Chronic restrictive: Post-tuberculosis destroyed lung; severe kyphoscoliosis	Chronic hypercapnia from a fixed restrictive defect	ABG; nocturnal SpO_2 / capnography; FVC	Chronic NIV (nighttime ± daytime); where feasible, primary NIV from the outset to avoid intubation	Transition from invasive MV to chronic NIV	Location-flexible: ICU if admitted there, otherwise step-down ward; → home NIV
MUSCLE	Acquired (ICU-AW / VIDD): Sepsis-related ICU-AW; VIDD; prolonged immobilization	Recoverable respiratory muscle weakness with systemic deconditioning	MIP / MEP; diaphragm ultrasound (thickening fraction); MRC sum score; PCF	Inspiratory muscle training (IMT); early mobilization; NMES when not mobilizable; PADIS-integrated care; nutritional optimization	SBT-based extubation once muscle reserve recovers (the SBT framework applies here)	ICU (SBT attempt first); if SBT fails, weaning continues in rehabilitation ward / weaning unit after sufficient rehabilitation
	NMD: Duchenne muscular dystrophy; ALS; Guillain-Barré syndrome; high cervical spinal cord injury; phrenic nerve injury	Non-recoverable or progressive respiratory muscle weakness	MIP / MEP; supine FVC; PCF; nocturnal capnography / SpO_2; bulbar assessment	NIV initiation and titration; MI-E for secretion management; where feasible, primary NIV from the outset to avoid intubation; if NIV fails → tracheostomy as bridge to NIV	Transition from invasive MV to NIV (not SBT-defined); decannulation when PCF and MIP stabilize	Location-flexible: ICU if admitted there, otherwise general / rehabilitation ward; respiratory rehabilitation center; home NIV

Table 1. Continued.

Category	Representative etiologies	Dominant pathophysiology	Domain-specific assessment	Ceiling intervention (cause-specific)	Weaning endpoint	Recommended weaning venue
BRAIN	Brainstem stroke (medulla / pons); hypoxic brain injury; post-cardiac arrest	Impaired central chemosensitivity and respiratory drive	Brainstem reflexes; level of consciousness; breathing-pattern observation; brainstem MRI; capnography; swallow / aspiration assessment (frequent overlap with the aspiration category)	Ventilator settings matched to impaired chemosensitivity (avoid hypocapnia; maintain baseline $PaCO_2$); removal of residual sedatives / opioids; treatment of demand-modifying factors (infection, pressure ulcers); cognitive rehabilitation during alert periods	Reliable spontaneous triggering under appropriate settings; acceptance of a new baseline (mild hypercapnia; supplemental O_2); a tracheostomy (T-tube) may be maintained where drive or airway protection does not recover	Rehabilitation ward / specialized weaning unit (out of ICU; weeks to months, within the 6–12 month recovery window)
ASPIRATION	Stroke; TBI; hypoxic brain injury; bulbar weakness (ALS, MG, late-onset NMD); Parkinson's disease; advanced age with sarcopenia	Failure of airway protection (swallow and cough)	VFSS; FEES; direct bulbar exam; PCF; clinical assessment of aspiration frequency and secretion burden	Swallowing therapy and oral hygiene; cough augmentation (manually-assisted cough, MI-E); salivary control (anticholinergics, botulinum toxin); tracheostomy as a manageable airway platform	Establishment of a managed airway platform (tracheostomy); decannulation considered only if cough and swallow function recover — not a guaranteed endpoint *	Out-of-ICU rehabilitation setting; long-term tracheostomy / care if airway protection does not recover

The framework comprises four categories (pulmonary, muscle, brain, aspiration); the pulmonary and muscle categories each contain two clinically distinct subgroups, shown as nested rows. Floor interventions — early mobilization, sedation minimization, nutritional optimization, and skin / joint care — apply universally to every ventilator-dependent patient regardless of etiology and are not repeated in each row. Recommended weaning venue denotes the clinical setting in which the weaning process is conducted, not the patient's final disposition: weaning in the acute pulmonary category is appropriately completed within the ICU, whereas for the remaining categories it need not be completed in the ICU and may proceed in settings beyond it.

* In the aspiration category, the weaning endpoint is defined by airway protection rather than ventilatory capacity. Because the representative etiologies include brain injury (stroke, TBI, hypoxic brain injury) in which airway protection may not recover, maintenance of a tracheostomy (T-tube) is frequently the appropriate long-term outcome; decannulation is pursued only when cough and swallow function recover sufficiently and is not a guaranteed endpoint.

ABG: arterial blood gas, ACBT: active cycle of breathing technique, ALS: amyotrophic lateral sclerosis, ARDS: acute respiratory distress syndrome, COPD: chronic obstructive pulmonary disease, FEES: fiberoptic endoscopic evaluation of swallowing, FVC: forced vital capacity, ICU: intensive care unit, ICU-AW: ICU-acquired weakness, IMT: inspiratory muscle training, MEP: maximum expiratory pressure, MG: myasthenia gravis, MI-E: mechanical insufflation-exsufflation, MIP: maximum inspiratory pressure, MRC: medical research council, MV: mechanical ventilation, NIV: non-invasive ventilation, NMD: neuromuscular disease, NMES: neuromuscular electrical stimulation, PADIS: pain, agitation/sedation, delirium, immobility, sleep, PCF: peak cough flow, PEP: positive expiratory pressure, P/F: PaO_2/FiO_2, RSBI: rapid shallow breathing index, SBT: spontaneous breathing trial, TBI: traumatic brain injury, VFSS: videofluoroscopic swallowing study, VIDD: ventilator-induced diaphragm dysfunction.

acute event (pneumonia, severe bronchitis), weaning often fails to progress even after the acute event has stabilized. The essence of weaning failure in these patients is not the acute event but the underlying chronic restrictive disease, and therefore the appropriate long-term solution after the acute phase is not continued invasive ventilation (i.e., tracheostomy) but introduction of chronic NIV. Nighttime NIV alone may suffice; even when 24-hour NIV is required, defaulting to the invasive route is difficult to justify. The principle that NIV constitutes the long-term solution for patients with chronically inadequate ventilatory capacity has been refined over decades by groups led by Bach and Kang in the NMD field [5,6] and may also apply to selected patients with chronic restrictive ventilatory failure such as post-tuberculosis destroyed lung, although the underlying pathophysiology differs from that of neuromuscular disease.

(2) Muscle

The muscle category, on its surface, appears to be a single category but in fact comprises two clinically distinct patient groups. The first comprises patients whose respiratory muscles have weakened as a consequence of acute illness or prolonged MV — ICU-acquired weakness (ICU-AW) or ventilator-induced diaphragm dysfunction (VIDD) — in whom muscle reserve is recoverable with appropriate intervention. The second comprises patients with underlying NMD such as Duchenne muscular dystrophy or ALS, in whom respiratory muscle weakness is non-recoverable or progressive and the clinical goal itself differs. The two groups share some evaluation tools, but the core of rehabilitation intervention and the endpoint of weaning diverge.

① **Acquired Muscle Weakness (ICU-AW, VIDD)**

The central insight in this patient group can be summarized in a single sentence: while we ventilate the lung, the diaphragm atrophies. Since Goligher and colleagues demonstrated that diaphragm thickness decreases to a clinically meaningful degree within days of starting controlled ventilation [7], VIDD has ceased to be a hypothesized phenomenon and has become a measurable clinical entity. The cruel paradox is that the more ventilatory support we provide a patient, the faster they lose the very muscle required for weaning.

Evaluation requires data not routinely measured in the ICU: maximum inspiratory pressure (MIP) and maximum expiratory pressure (MEP), diaphragm ultrasound including thickening fraction, the MRC sum score for global muscle strength assessment, and — overlapping with the aspiration category — peak cough flow [8].

Rehabilitation intervention comprises two axes. The first is inspiratory muscle training (IMT), which acts directly on the respiratory muscles. Recent meta-analyses have consistently shown that IMT shortens weaning time and increases successful liberation [8]. The second is the broader domain known as ICU rehabilitation or critical care rehabilitation, which has rapidly attracted clinical attention in recent years. As the recognition has solidified that ICU-AW is fundamentally not weakness of a single muscle but a systemic deconditioning, the focus of rehabilitation has expanded beyond the diaphragm to whole-body strength and function. Early mobilization is the central intervention in this domain — evidence has accumulated that minimizing sedation as much as possible and progressively advancing the patient through sitting, standing, and ambulation in an awake state reduces the incidence of ICU-AW and improves functional outcomes [9]. In patients for whom active mobilization is difficult, neuromuscular electrical stimulation (NMES) is used adjunctively. To these are added nutritional optimization and sedation minimization — components of the integrated PADIS framework that addresses Pain, Agitation/sedation, Delirium, Immobility, and Sleep [9].

The clinical goal in this patient group is clear: recovery of muscle reserve and liberation from the ventilator. SBT failure here is not a lung problem but a muscle problem, and therefore the answer is not to wait for lung recovery but to train the muscle and prevent systemic deconditioning.

② **Neuromuscular Disease**

In NMD patients, the clinical goal itself differs from that in acquired weakness. Respiratory muscle weakness is non-recoverable or progressive, and beyond a certain point ventilatory support becomes necessary. The clinical goal in this patient group is therefore not weaning from the ventilator but introduction and maintenance of appropriate ventilator support. NIV is initiated at the appropriate time to support the patient's alveolar ventilation, secretion management is addressed in parallel through mechanical insufflation-exsufflation (MI-E) [10] and related modalities, and progression to daytime ventilation is decided in stages according to disease trajectory. This approach has been refined over decades by groups led by Bach and Kang in NMD [5,6], with long-term outcomes over five or more years exceeding those of invasive ventilation in domains where comparison has been reported.

When an NMD patient is admitted to the ICU and intubated for an acute event (aspiration pneumonia, anesthesia, etc.), clinical decision-making is particularly important. The lung in these patients is generally preserved; the underlying reason for intubation is not lung disease but a transient worsening of chronic muscle weakness due to the acute event. The appropriate path in this case is not continued invasive ventilation but direct transition to NIV after stabilization of the acute event. If NIV substitutes for the inspiratory pressure that the ventilatory muscles cannot generate and MI-E supports secretion management, direct extubation becomes feasible [5,6]. In such cases, the meaning of weaning is not passing an SBT but transitioning from invasive ventilation to NIV.

A practical bedside checklist of general readiness items for initiating direct extubation in this population is summarized in Table 2; NMD-specific protocol features are discussed in the paragraph that follows.

The NMD-specific extubation protocol established by Bach and colleagues differs from conventional weaning criteria in several clinically important respects, and these distinctions warrant emphasis [5,11]. First, oxygenation criteria are assessed on ambient air: a persistent supplemental oxygen requirement is interpreted as evidence that the acute pulmonary insult is not yet resolved, and constitutes a contraindication to extubation rather than a baseline support to be tolerated. Second, and more counter-intuitively, supplemental oxygen remains contraindicated after extubation as well — a fall in oxygen saturation in these patients is addressed not by oxygen administration but by MI-E and air-stacking maneuvers to clear secretions and restore alveolar ventilation. The rationale is that supplemental oxygen in NMD patients can mask underlying hypercapnia and further depress an already vulnerable respiratory drive. Third, extubation proceeds directly to full-setting NIV — typically high-span inspiratory pressure with mandatory backup rate — rather than through a graded reduction of ventilator support; the concept of a “trial of decreasing support” central to SBT-based weaning has no place in this protocol. Fourth, the cough criterion is defined in terms of assisted peak cough flow (≥ 160 L/min, with ≥ 270 L/min preferred), achieved with MI-E or manually-assisted cough rather than spontaneous cough alone. These distinctions are not minor procedural differences but reflect a fundamentally different conception of what extubation means in this patient population.

If the initial NIV trial does not succeed — that is, if meaningful ventilator-free time cannot be secured — tracheostomy is considered. Even then, however, tracheostomy is not a lock-in to permanent invasive ventilation but a step that, after step-down to a setting outside the ICU, attempts ultimate transition to NIV through bridge weaning — a staged weaning process in which the tracheostomy serves as a temporary platform for stabilizing respiratory mechanics and secretion management before final transition to non-invasive support. Weaning at this stage proceeds not as protocol SBTs but as progressive trials, since the recovery (or stabilization) of muscle reserve operates on a timescale of weeks to months rather than days. When peak cough flow and MIP reach stable levels, decannulation is attempted and the patient transitions to home NIV [11].

In short, the clinician's question in NMD is not "when do we wean?" but "what ventilator support, introduced at what

Table 2. Bedside Checklist for Direct Extubation to NIV in Neuromuscular Disease (NMD) Patients Admitted to the ICU for an Acute Trigger.

Underlying premise: This checklist assumes the defining condition of the NMD weaning scenario - the lung parenchyma is preserved, and intubation was driven by a transient worsening of chronic muscle weakness (e.g., from an acute infection) rather than by lung disease itself.

Domain	Specific criterion	Comment
1. Resolution of acute trigger	Acute infection (pneumonia, sepsis) improving: declining CRP / procalcitonin trend; afebrile ≥ 24 h; hemodynamic stability without vasopressors; chest imaging stable or improving	The acute event — not the underlying NMD — must be resolving; the underlying NMD itself is not expected to recover
2. Consciousness and cooperation	Alert enough to cooperate with care: able to follow the care team's instructions and coordinate with NIV interface application and cough augmentation therapy (manually-assisted cough and/or MI-E); intermittent sedation acceptable if the patient is cooperative when awake	NIV and cough augmentation success depends on the patient's ability to cooperate with the care team; a specific sedation score is less important than reliable cooperation when awake
3. Gas exchange targets	Under the intended post-extubation support (full-setting NIV), gas exchange remains within target: $SpO_2 \geq 95\%$ on ambient air (a persistent supplemental O_2 requirement indicates an unresolved acute insult); $PaCO_2$ at or near the patient's chronic baseline (individualized; absolute normalization not required); pH ≥ 7.35	Because lung parenchyma is preserved in this scenario, maintenance of gas-exchange targets on NIV — not on the ventilator — confirms the acute insult has resolved and that ventilatory-muscle support alone now suffices; failure to hold targets on NIV signals an unresolved pulmonary problem. Chronic hypercapnia is the baseline in many NMD patients, so $PaCO_2$ normalization is not required.
4. Airway protection	Adequate cough: assisted peak cough flow (PCF) ≥ 160 L/min (ideally ≥ 270 L/min); manageable bulbar function (no severe oral pooling); able to handle oral secretions	Insufficient cough is the most common cause of NIV failure; effective cough augmentation (manually-assisted cough and/or MI-E) should be established and confirmed effective before extubation, with the assisted PCF threshold serving as the practical benchmark
5. NIV readiness	NIV interface fitted (oronasal or nasal mask, individualized); initial ventilator settings selected and then titrated to response (full-setting NIV: high-span inspiratory pressure with mandatory backup rate); cough augmentation therapy available; established home NIV users are often already adapted and need little additional preparation, whereas NIV-naive patients require a planned adaptation period and close monitoring for interface intolerance, asynchrony, and secretion-handling difficulty	Settings are adjusted iteratively rather than fixed in advance. Patients already established on home NIV are typically adapted and require minimal additional readiness work. NIV-naive patients are the higher-risk group: a pre-extubation adaptation trial, interface and synchrony optimization, and a low threshold for early support escalation should be planned in advance. Caregiver training on the interface and cough augmentation proceeds in parallel where applicable.
6. Destination-ward readiness	Arranged as part of the extubation plan: NIV device and cough augmentation therapy available; nursing / respiratory-therapy staff oriented to their use; a physiatrist or pulmonologist accessible for adjustment; escalation / transfer pathway agreed in advance	Unlike the patient-side items, this is a system-level factor — and an underrecognized contributor to failed NMD extubation when overlooked. The point is not that extubation is permissible only in fully-equipped wards, but that ward readiness should be arranged in advance alongside patient readiness, through targeted staff orientation or involving the rehabilitation / pulmonary team in the transfer. Where the team is not confident that adequate NIV and cough-augmentation support can be provided, referral to a center experienced in neuromuscular respiratory care is the appropriate and safe option rather than proceeding and managing failure reactively.

Table 2. Continued.

Domain	Specific criterion	Comment
7. Contingency plan	Reintubation criteria pre-specified (refractory hypercapnia with worsening sensorium; hemodynamic instability; secretion management failure despite cough augmentation); escalation pathway documented, consistent with the transfer / referral plan in item 6	Predefined criteria reduce delayed reintubation and prevent inappropriate prolongation of NIV in failing patients

Items 1–5 address the patient; item 6 addresses destination-ward readiness; item 7 establishes the safety net. Cough augmentation therapy denotes manually-assisted cough and/or mechanical insufflation-exsufflation (MI-E); the specific modality is individualized rather than fixed to a single device.
CRP: C-reactive protein. MAC: manually-assisted cough, MI-E: mechanical insufflation-exsufflation, NIV: non-invasive ventilation, NMD: neuromuscular disease, $PaCO_2$: partial pressure of carbon dioxide in arterial blood, PCF: peak cough flow, SpO_2: peripheral oxygen saturation.

time?" This question lies fundamentally within the domain of rehabilitation medicine, and it is the central decision in long-term care that proceeds outside the ICU.

(3) Brain

The mechanisms by which weaning fails to progress in the brain category fall broadly into two patterns. The first is impairment of the system driving respiration itself due to brainstem injury; the second is recurrent aspiration pneumonia obstructing weaning. The latter is fundamentally a problem of airway protection and is therefore addressed in the aspiration section (4.4); this section focuses on the former — impairment of central respiratory drive.

In these patients, appropriate adjustment of ventilator settings is clinically critical. The reason is as follows. Normal respiratory regulation is driven by the rise of $PaCO_2$ as a stimulus, but in patients with damage to brainstem chemoreceptors or their higher integrative circuits, this feedback loop is weakened [12,13]. In this state, hyperventilation — whether intentional or inadvertent — that lowers $PaCO_2$ below normal further suppresses an already-weakened respiratory drive, and the patient ceases to trigger spontaneous breaths. This is observed clinically as patient "apnea" and gives the impression that extubation or ventilator weaning is impossible. In reality, however, this is not because the patient's respiratory capacity itself is insufficient, but because the ventilator settings do not match the patient's impaired chemosensitivity.

The clinical manifestations of this mechanism are varied. Cheyne-Stokes respiration is the more familiar pattern, but more irregular ataxic patterns such as Biot respiration are also common. Such breathing patterns should be interpreted not as evidence that the patient "cannot" wean, but as the result of a mismatch between the impaired drive and the ventilator settings.

Accordingly, when managing mechanical ventilation in brain-category patients, the clinician should ask two questions in sequence.

First, is the patient's lesion actually one expected to involve respiratory center damage? If the lesion is not a stroke or hypoxic brain injury involving the brainstem — particularly the medulla or pons — abnormal breathing patterns are more likely to reflect not a problem of the respiratory center itself but of accompanying pneumonia or bulbar muscle weakness. In such cases, the clinical justification for continuing the ventilator is weak, and weaning from the ventilator is often achievable simply through tracheostomy to secure the airway and manage secretions. In other words, not all patients in the brain category require the same strategy; primary differentiation begins with lesion-based assessment. Patients without respiratory center involvement should in fact be managed in a manner closer to the aspiration category (Section 4.4).

Second, when the lesion is confirmed or strongly suspected to involve the respiratory center, the clinical framing itself must shift. The key points are as follows.

(i) Although brainstem plasticity has been reported to be more limited than that of other brain regions, the capacity for recovery is preserved [14]. Acute brain injuries — stroke, traumatic brain injury, hypoxic brain injury — generally follow a recovery trajectory over approximately six months to one year [15], and the brainstem's respiratory driving circuits may fall within that recovery window. Some patients ultimately require chronic ventilation; others do not. Locking in chronic ventilator dependence before this six- to twelve-month recovery window — based solely on the abnormal breathing pattern — is a premature decision and may deprive recoverable patients of that possibility.

(ii) Covert factors that elevate ventilatory demand commonly accompany these patients. Underlying bronchitis, urinary tract infection, and pressure ulcers — chronic infectious burdens of this kind — chronically raise respiratory demand and contribute to maintained ventilator dependence. In some patients, recognition and treatment of these demand-modifying factors may be sufficient to permit ventilator liberation.

(iii) The ventilator settings themselves must align with the patient's impaired chemosensitivity. In selected patients, avoiding inadvertent hypocapnia and maintaining $PaCO_2$ near the patient's baseline may help preserve the weakened respiratory drive and improve triggering of spontaneous breaths. This is a simple but clinically important setting decision.

(iv) In the author's clinical experience, supplemental oxygen is not infrequently required in these patients even after liberation from positive-pressure ventilation, often reflecting coexisting atelectasis, secretion burden, ventilation-perfusion mismatch, or recurrent low-grade aspiration in addition to the central drive abnormality. In tracheostomized patients, oxygen is generally delivered via the T-tube. Recognizing this oxygen requirement as part of a new clinical baseline, rather than as automatic evidence of failed weaning, is appropriate.

While a comprehensive case-by-case account of ventilator management in this category is beyond the scope of this conceptual review, several practical principles can be articulated. In selected brainstem-injury patients, initial ventilator settings should emphasize a backup mode (e.g., pressure support with mandatory backup rate or pressure-controlled ventilation), with target $PaCO_2$ titrated toward the patient’s pre-injury baseline rather than toward standard normocapnia. Avoidance of inadvertent hypocapnia, which can further suppress an already weakened drive, is more important than absolute target values. When Cheyne-Stokes or other irregular patterns emerge, upward adjustment of the backup rate stabilizes minute ventilation while preserving the patient’s residual triggering capacity. Nocturnal hypoventilation, common in this population, may require independent backup support even when daytime breathing appears adequate. Detailed case-series description of ventilator management strategies and venue-decision pathways in brainstem-injury patients — including stepwise illustration of the diagnostic, tracheostomy-timing, and transfer decisions across representative cases — is the subject of a forthcoming report by the author.

Accordingly, evaluation in this category should include brainstem reflexes, level of consciousness, quantitative and qualitative observation of breathing patterns, brainstem MRI, and capnography for hypoventilation assessment. Rehabilitation interventions consist of removal of reversible factors (residual sedatives, opioids), active treatment of demand-modifying factors (infection, pressure ulcers), management of the underlying lesion, and cognitive rehabilitation utilizing periods when the patient is alert.

The weaning strategy is one of patience. The three axes outlined above — allowing time for plasticity, treating demand-modifying factors, and appropriately calibrating settings — are applied in an integrated manner while the patient is safely supported on a ventilator with a backup mode. Trial weaning proceeds on a timescale of weeks to months rather than days, and during the typical six- to twelve-month recovery window for brain injury, deferring the decision regarding chronic ventilator dependence and keeping the possibility open is reasonable. This timeline does not match the ICU environment, and weaning in these patients need not be completed within the ICU — it should be understood as a domain of care that may proceed over an extended period in settings outside the ICU.

(4) Aspiration

The aspiration category, as emphasized earlier, frequently overlaps with the other three categories but warrants separate organization because its evaluation and intervention axes differ. Whereas problems of the lung, muscle, and brain are failures of respiration or of the systems that drive it, aspiration operates on a different axis — the patient's inability to protect their own airway.

The core point is clear: the tube is not the problem; secretions are. In these patients, lowering ventilator settings or repeating SBTs does not advance weaning. Even when extubated, the patient soon requires reintubation due to aspiration or secretion blockage. This is neither a mechanical problem nor a gas exchange problem. It is because the patient cannot manage secretions or prevent aspiration.

Evaluation in this category proceeds along an axis entirely different from the other three. The core is assessment of the patient's airway protection capacity — that is, swallow function and cough function. Videofluoroscopic swallowing study (VFSS) or fiberoptic endoscopic evaluation of swallowing (FEES) provides objective evaluation of the degree and pattern of aspiration, and direct bulbar examination confirms oral motor function. International guidelines on post-stroke dysphagia have likewise endorsed instrumental swallow evaluation as the standard for objective characterization in patients at risk of aspiration [16]. Clinical evaluation of aspiration frequency and secretion burden should be added.

Rehabilitation interventions consist of swallowing therapy and oral hygiene, cough augmentation (manually-assisted cough, mechanical insufflation-exsufflation), and, when needed, control of salivary secretion (anticholinergic medications, botulinum toxin injection, etc.). The clinically clearest decision in patients who cannot protect their airway is not repeated SBTs but establishment of a manageable airway, and tracheostomy provides such a platform. Cuff inflation can reduce gross aspiration into the lower airway, above-cuff or subglottic suctioning can decrease pooled secretions, and direct airway access enables repeated suctioning and structured cough augmentation [17]. Tracheostomy does not eliminate aspiration risk — microaspiration and leakage around the cuff remain possible — but it converts an uncontrolled aspiration problem into a manageable airway-protection problem, often outside the ICU. A clinically important point is that, in some of these patients, the ventilator was not necessary in the first place. In some cases, bulbar weakness and airway-protection failure may be clinically framed as respiratory failure, leading to intubation and mechanical ventilation even when the primary need is airway management rather than ventilatory support. In such cases, accurate diagnosis followed by tracheostomy to secure airway access makes the ventilator itself unnecessary. What the patient required was not ventilatory support but airway protection.

The weaning strategy diverges decisively from that of the other categories. Repeating SBTs is not the answer. The answer is a prompt decision regarding tracheostomy and transfer out of the ICU. NIV is generally inappropriate, since it does not provide airway protection. The timeline is long — weeks to months. These patients should not remain in the ICU; in an appropriate setting, the recovery of cough function and swallow function should be evaluated over time, and the possibility of decannulation considered.

4) Venue Decision: ICU and Beyond

A natural conclusion follows from the four-category framework presented above. Among the four etiologies, ICU-based weaning works best for the pulmonary category; for the other three — muscle, brain, and aspiration — weaning need not be completed within the ICU. For these patients, weaning is a domain of care that may proceed over an extended period in settings outside the ICU — the general ward, rehabilitation ward, specialized weaning unit, or home.

The clinical implications of this venue distinction extend beyond simple administrative transfer. The ICU environment itself can be unhelpful or even an obstacle to weaning. First, regarding sedation: the ICU environment, with its endotracheal tube and continuous monitoring, makes aggressive sedation reduction difficult. In settings outside the ICU (general ward, rehabilitation ward, or specialized weaning unit), patients can regain consciousness and become capable of mobilization. Second, regarding actual rehabilitation: dysphagia rehabilitation, NIV training, brain rehabilitation, and active exercise are interventions difficult to attempt within the ICU environment. Third, regarding timeline: the ICU is an environment designed in days, but patients in the muscle, brain, and aspiration categories require recovery on the order of weeks or months. The two timescales do not align well.

The data reported by Scheinhorn and colleagues from a post-acute weaning center empirically support this venue argument [18,19]. More than 50% of patients judged "unweanable" in the ICU eventually achieved liberation after transfer to a post-acute setting. The NAMDRC consensus statement on prolonged mechanical ventilation similarly recognized that this patient population requires care models distinct from those of acute critical care [20]. That is, these patients were not unable to wean per se; they had been placed in the wrong setting. Such data suggest more than simply that "some patients wean outside the ICU" — they suggest that a patient's likelihood of weaning differs meaningfully according to setting.

The position of tracheostomy also warrants reconsideration here. In clinical culture — among patients, families, and clinicians alike — tracheostomy is often perceived as a marker of weaning failure. For patients in the muscle, brain, and aspiration categories, however, tracheostomy is not a marker of defeat but a clinical decision point that converts ICU-bound weaning into active rehabilitation. After tracheostomy, sedation can be reduced, the patient becomes alert, and communication and mobilization become possible. In addition, domains that were difficult to attempt while the endotracheal tube was in place — activities of daily living such as ambulation, active exercise therapy, and rehabilitation reflecting the patient's own volition — become feasible. The decision regarding the appropriate timing of tracheostomy and the design of the rehabilitation pathway thereafter constitute clinical contributions of rehabilitation medicine.

5) The Role of Rehabilitation Medicine

The framework proposed in this review is not intended to replace standard weaning protocols but to organize the complementary contributions that rehabilitation medicine can make in domains where those protocols struggle. In pulmonary-category patients, the framework established by pulmonology and critical care remains primary, although rehabilitation medicine contributes through mobilization, airway clearance, and prevention of deconditioning. In the other three categories — muscle, brain, and aspiration — rehabilitation medicine offers specific tools that can produce clinical outcomes difficult to reach with protocol-driven approaches alone.

The category-specific contributions of rehabilitation medicine — inspiratory muscle training and early mobilization in the muscle category; recalibration of temporal expectations and acceptance of a new physiologic baseline in the brain category; structured swallow and cough evaluation and decannulation pathway design in the aspiration category — have been detailed in Section 4 and summarized in Table 1. The common thread across these contributions is a shift in clinical framing: from a question of whether the patient passes a defined endpoint within a defined time, to a question of which combination of interventions, in which setting, over which timescale, advances the patient toward functional liberation. This framing is the distinctive contribution that rehabilitation medicine brings to the territory where SBT-based protocols stall.

In this context, referral to rehabilitation medicine should be considered as early as possible in patients in whom standard weaning protocols stall. Such referral can clarify the patient's dominant etiology, apply the appropriate evaluation tools, and design transition to an appropriate venue. This is not a competition between protocols and rehabilitation medicine but a division of labor — a collaborative framework for the patient's clinical outcome [17].

Conclusion

Liberation from mechanical ventilation has long been approached as a problem of protocol, and that framework works well for patients with pulmonary problems. Not every ventilator-dependent patient, however, is on the ventilator because of a lung problem. In this review, the author has proposed a complementary framework that classifies ventilator-dependent patients into four categories — pulmonary, muscle, brain, and aspiration — according to the dominant etiology of their ventilator dependence. In the three categories other than pulmonary, standard SBT protocols are not the primary tool, and a different approach is required across evaluation, intervention, and venue.

The clinical implication of this framework is straightforward. Weaning failure in many cases is not the result of protocol inadequacy but of a missed diagnosis of the dominant etiology. And that diagnostic mismatch frequently leads to a venue mismatch — a patient in whom weaning cannot easily advance in the ICU remaining in the ICU. For three of the four etiologies, weaning need not be completed within the ICU and is a domain of care that may proceed over an extended period in settings outside it. It is in this domain that rehabilitation medicine can offer clinical contributions that protocol-driven approaches cannot reach.

This review is offered not to displace the standard weaning framework but to provide a complementary lens for the patient population that framework does not serve well. Approach lung problems with tools for the lung, muscle problems with tools for muscle, brain problems with tools for the brain, and aspiration problems with tools for airway protection — this is the simple principle proposed by the present framework. In many patients, the answer to the final question of weaning — “where will weaning take place?” — may not be the ICU, and that recognition is the first step in the clinical pathway that brings the patient where they need to be.

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