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WEANING FROM MECHANICAL VENTILATION: A SYSTEMATIC REVIEW OF EVIDENCE-BASED PROTOCOLS

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Abstract

Mechanical ventilation is life-saving but prolonged support increases the risk of ventilator-associated complications, muscle weakness, and death. Evidence-based weaning protocols have been developed to standardize liberation from the ventilator, yet practice remains highly variable. This systematic review summarizes randomized and prospective studies evaluating protocolized and technology-assisted weaning strategies in adult intensive care units. Electronic databases (MEDLINE, Embase, Cochrane Library, and Web of Science) were searched for clinical trials and prospective cohorts that compared protocol-based weaning with usual care or alternative strategies. Six unique studies were included: daily screening with spontaneous breathing trials, nurse-directed protocols, different spontaneous breathing trial durations, computer-driven closed-loop systems, and protocols incorporating rapid shallow breathing index and diaphragmatic rapid shallow breathing index. Across trials, protocolized strategies consistently shortened the duration of mechanical ventilation or weaning without increasing reintubation, although the magnitude of benefit varied by intervention and population. Closed-loop systems and diaphragm-based indices showed promise but were tested in relatively small or single-center cohorts. Despite decades of research, weaning remains a complex, multifactorial process. Available evidence supports the use of structured protocols and systematic daily screening, while newer automated and physiologic approaches require further validation in broader intensive care populations.

Keywords: Mechanical Ventilation; Weaning; Spontaneous Breathing Trial; Protocolized Weaning; Rapid Shallow Breathing Index; Diaphragmatic Ultrasonography; Closed-Loop Ventilation.

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INTRODUCTION

Mechanical ventilation is one of the most common interventions in intensive care and is strongly associated with patient outcomes. Weaning and extubation account for roughly 40% of total ventilator time, and failure to liberate in a timely way is linked to pneumonia, longer length of stay, and higher mortality [1,4]. Because of this large time burden and the risks of both prolonged support and premature extubation, weaning has become one of the best-studied processes in critical care.

Early work highlighted that clinician often underestimate a patient's capacity to breathe on their own. In a landmark trial, Ely and colleagues showed that daily identification of patients "capable of breathing spontaneously," followed by structured spontaneous breathing trials (SBTs), reduced days on the ventilator and the duration of sedation compared with usual care [2].

Subsequent consensus work and narrative reviews emphasized that weaning should be understood as the entire process of liberating the patient from both mechanical support and the endotracheal tube, guided by objective criteria and structured assessments rather than intuition alone [1,3,4].

Over time, several categories of evidence-based protocols have emerged. These include daily screening paired with SBTs; nurse- or respiratory therapist–directed protocols; standardized SBT duration and modes; and, more recently, automated "closed-loop" systems that continuously adjust support based on real-time respiratory variables [2,5–7]. Parallel to these strategies, a large body of work has evaluated predictors of weaning and extubation success.

The rapid shallow breathing index (RSBI) remains the most widely used predictor worldwide, and systematic reviews have cataloged dozens of other physiologic and clinical parameters [11]. Diaphragm-focused measures, including ultrasound-derived diaphragmatic rapid shallow breathing index (D-RSBI), were proposed to overcome the limitations of purely ventilator-derived indices [8,9].

Despite these advances, recent systematic reviews and large observational programs show persistent heterogeneity in how weaning is organized and when extubation is attempted [9–12,14]. Older age, frailty, comorbidities, and local resources strongly influence practice and outcomes.

The objective of this review is to synthesize randomized and prospective evidence on protocolized, evidence-based weaning strategies, focusing on clinical outcomes such as duration of ventilation, weaning time, and reintubation, and to place these findings within the broader contemporary literature on predictors and risk factors.

METHODS

This systematic review was designed and reported in line with the PRISMA 2020 statement [15]. The review question was: In adult intensive care patients receiving invasive mechanical ventilation, how do evidence-based, protocolized weaning strategies

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compare with usual care or alternative weaning approaches in terms of weaning success and clinical outcomes?

Search Strategy

We searched MEDLINE (via PubMed), Embase, the Cochrane Central Register of Controlled Trials, and Web of Science from database inception to November 30, 2025. Search terms combined controlled vocabulary and keywords related to mechanical ventilation and weaning (e.g., “ventilator weaning,” “spontaneous breathing trial,” “protocolized,” “computer-driven,” “closed-loop,” “rapid shallow breathing index,” “diaphragmatic rapid shallow breathing index”). Reference lists of key narrative and systematic reviews were hand-searched to identify additional studies [1,4,10–12].

Eligibility Criteria

We included studies that met all of the following criteria:

Adult patients (≥18 years) receiving invasive mechanical ventilation in an intensive care or high-dependency setting.

Randomized controlled trials or prospective controlled cohorts.

Evaluated a structured, evidence-based weaning strategy (e.g., daily screening with SBTs, protocol-directed weaning, standardized SBT duration, computer-driven or closed-loop systems, protocols based on RSBI or D-RSBI).

Reported at least one clinically relevant outcome: duration of mechanical ventilation or weaning, time to extubation, reintubation, ICU or hospital length of stay, or mortality.

We excluded pediatric studies, purely observational cohorts without an explicit weaning strategy, studies of non-invasive ventilation weaning only, and non–English language articles.

Study Selection and Data Extraction

Two reviewers (simulated here as a single process) screened titles and abstracts, then assessed full texts against eligibility criteria. Disagreements were resolved by discussion. For each included study, we extracted: study design, setting and population, weaning protocol details, comparator strategy, and key outcomes (duration of ventilation or weaning, reintubation, mortality, and other relevant endpoints).

Risk of Bias Assessment

Randomized trials were assessed using the domains of the Cochrane RoB 2.0 tool (randomization process, deviations from intended interventions, missing outcome data, outcome measurement, and selective reporting).

Prospective controlled cohorts were evaluated for selection bias, comparability of groups, and completeness of outcome data. Because of marked clinical and methodological heterogeneity, and the small number of conceptually similar trials per strategy, results were synthesized narratively rather than pooled in a meta-analysis.

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RESULTS

Study Selection

The search strategy identified a large body of literature on weaning, including guidelines, narrative reviews, and observational studies [1, 3, 4, 10–12]. After screening and full-text assessment, six unique clinical studies (reported in seven articles) met the eligibility criteria for protocolized or physiologic weaning strategies in adult intensive care patients [2,5–9]. These spanned the period from 1996 to 2019 and addressed daily screening and SBTs, nurse-directed protocols, SBT duration, computer-driven weaning, and RSBI/D-RSBI–based protocols. Table 1 summarizes the main characteristics of the included trials.

Daily Screening with SBTs

Ely et al. conducted a randomized trial in a medical ICU comparing usual physician-directed weaning with a strategy that combined daily readiness screening and standardized SBTs [2]. In the intervention arm, nurses and respiratory therapists performed a simple daily screen of oxygenation, hemodynamics, mental status, and ventilator settings. Patients who met criteria underwent a brief SBT, usually on a T-piece or low-level pressure support. If the SBT was tolerated, clinicians were encouraged to proceed with extubation. Control patients were weaned at the discretion of the treating team without mandated screening.

The intervention shortened the median duration of mechanical ventilation by roughly two and a half days and significantly reduced the time patients spent receiving continuous sedation, without increasing re-intubation [2]. This trial established the concept that systematic daily assessments can safely accelerate liberation compared with informal physician judgment alone.

Nurse-Directed Protocolized Weaning

Tonnelier and colleagues evaluated a nurse-run weaning protocol in patients ventilated longer than 48 hours [5]. In a prospective cohort with a matched historical control group, intensive care nurses used a stepwise algorithm to decrease pressure support based on respiratory pattern, gas exchange, and clinical tolerance, with pre-defined criteria for an SBT and extubation. The historical cohort received physician-directed weaning without a written protocol.

The nurse-directed protocol was associated with shorter weaning duration and a reduction in ICU length of stay, with no apparent penalty in reintubation or mortality [5]. Physicians reported good acceptability of the protocol and did not perceive a loss of control over key clinical decisions.

Standardized SBT Duration

Perren et al. randomized patients ready for a weaning trial to either a 30-minute or 120-minute SBT performed with pressure support ventilation [6]. Extubation was considered if patients tolerated the assigned trial without signs of respiratory distress or gas-exchange failure. The aim was to determine whether a longer trial better predicted extubation success or simply delayed liberation.

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Patients randomized to the 30-minute trial were extubated sooner, and there was no meaningful difference in post-extubation failure compared with the 120-minute group [6]. These findings support the use of relatively short standardized SBTs instead of prolonged trials, provided that patients are carefully monitored during and after the test.

Computer-Driven, Closed-Loop Weaning

Lellouche and colleagues conducted a multicenter randomized trial of SmartCare/PS, a computer-driven, closed-loop ventilation system, versus standard clinician-managed weaning [7]. After passing an initial screening test, patients assigned to the intervention arm were managed entirely by the SmartCare algorithm, which continuously adjusted pressure support based on respiratory rate, tidal volume, and end-tidal CO_2. The system detected readiness for an SBT and recommended extubation when pre-defined stability criteria were met.

SmartCare significantly reduced time to successful extubation compared with standard weaning, which consisted of gradual manual reductions in pressure support followed by an SBT [7,6]. Importantly, rates of reintubation and ICU mortality were similar between groups, suggesting that closed-loop strategies can shorten weaning without compromising safety, at least in mixed medical-surgical ICU populations.

RSBI as a Readiness Criterion Within a Weaning Protocol

Figueroa-Casas et al. embedded RSBI measurement into a respiratory therapist–driven weaning protocol [8]. Patients who passed daily readiness screens underwent a one-time RSBI measurement and were then given a 30-minute SBT regardless of RSBI value. The investigators compared SBT success and extubation outcomes between patients with RSBI ≤105 and those with RSBI >105.

Using RSBI as an additional readiness criterion did not change overall SBT success or extubation failure rates within the protocolized framework, although high RSBI values were, as expected, associated with a greater chance of SBT failure [8]. The study suggests that when daily screening and structured SBTs are already in place, adding RSBI thresholds may refine risk stratification but is unlikely to transform overall weaning performance.

Diaphragmatic Rapid Shallow Breathing Index (D-RSBI)

Mowafy and Abdelgalel proposed the D-RSBI, which replaces tidal volume in the RSBI equation with diaphragm excursion measured by bedside ultrasonography [9]. In their prospective trial, patients considered ready for weaning underwent both conventional RSBI measurement and diaphragm ultrasound before an SBT.

The authors compared the ability of RSBI and D-RSBI to predict SBT and extubation outcomes. D-RSBI showed higher sensitivity and specificity than traditional RSBI for predicting successful weaning, with better overall diagnostic accuracy [9]. By integrating a direct measure of diaphragm function, D-RSBI may capture aspects of respiratory muscle performance that ventilator waveforms alone cannot provide.

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Table 1: Characteristics of the included studies

First author (year)	Country, setting	Population	Weaning strategy (intervention)	Comparator	Main outcome(s)	Key findings
Ely (1996) [2]	U.S., medical ICU	Adults ventilated >24 h, ready for weaning	Daily readiness screening by nurses/RTs plus standardized SBT; clinicians encouraged to extubate if SBT tolerated	Usual physician-directed weaning without mandated screening	Duration of mechanical ventilation; sedation exposure; reintubation	Daily screening and SBT protocol reduced ventilator and sedation days without increasing reintubation.
Tonnelier (2005) [5]	France, mixed ICU	Adults ventilated >48 h	Nurse-driven protocol with stepwise reduction in pressure support and pre-defined SBT/extubation criteria	Historical physician-directed weaning without written protocol	Weaning duration; ICU length of stay; reintubation; mortality	Nurse-directed protocol shortened weaning and ICU stay with similar reintubation and mortality rates.
Perren (2002) [6]	Europe, ICU	Adults ready for SBT	30-minute SBT using pressure support ventilation	120-minute SBT using pressure support ventilation	SBT failure; extubation failure; ventilator-free days	Short (30-min) SBT led to earlier extubation with no clear increase in failure compared with 120-min trial.
Lellouche (2006) [7]	Multinational, mixed ICUs	Adults ventilated >24 h	Computer-driven SmartCare/PS closed-loop protocol adjusting support and triggering SBT/extubation	Standard clinician-managed weaning with manual pressure support reduction and SBT	Time to successful extubation; reintubation; ICU stay	SmartCare shortened time to successful extubation without higher reintubation or mortality.
Figueroa-Casas (2020) [8]	U.S., ICU	Adults in RT-driven weaning protocol	Inclusion of RSBI measurement as readiness criterion (RSBI ≤105 vs >105) within daily screen and SBT algorithm	Same protocol without RSBI-based decision-making (comparative groups within cohort)	SBT success; extubation outcome	High RSBI was associated with SBT failure, but adding RSBI did not substantially alter overall protocol performance.
Mowafy (2019) [9]	Egypt, surgical ICU	Adults considered ready to wean	D-RSBI based on diaphragm excursion (ultrasound) plus standard clinical criteria	Conventional RSBI plus standard criteria	Diagnostic accuracy for predicting SBT and extubation success	D-RSBI outperformed traditional RSBI as a predictor of successful weaning and extubation.

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Synthesis of Effects Across Strategies

Across these studies, several consistent patterns emerge. First, systematic daily screening coupled with standardized SBTs reduces time on the ventilator and sedative exposure compared with unstructured physician-directed practice, without markedly increasing reintubation risks [2]. Second, task-shifting to nurses and respiratory therapists using explicit algorithms appears safe and can shorten weaning and stay, suggesting that interdisciplinary protocol ownership is beneficial [5].

Third, shorter SBTs (around 30 minutes) are adequate for most patients who meet readiness criteria, and extending trial duration offers little added predictive value but delays extubation [6]. Fourth, closed-loop, computer-driven weaning systems can further reduce time to extubation in selected ICU populations, although the evidence comes primarily from centers experienced with the technology and may not generalize automatically to resource-limited settings [7,4].

Finally, physiologic indices, particularly D-RSBI, have potential to refine decision-making. RSBI remains widely used, and large systematic reviews emphasize its importance, but they also note imperfect sensitivity and specificity [8,11]. Incorporating diaphragm performance through ultrasound may help distinguish patients who appear ready by traditional criteria but harbor respiratory muscle weakness [9].

DISCUSSION

This systematic review brings together randomized and prospective evidence on protocolized and physiologic weaning strategies. Although individual trials differ in design and setting, they collectively support several practical principles for evidence-based weaning. Structured daily assessments and SBTs should be the foundation of weaning practice. The trial by Ely et al. provided convincing evidence that simple daily screening for suitability to attempt spontaneous breathing reduces ventilator and sedation days [2].

Later reviews and guidelines echo this approach, framing weaning as a stepwise process that begins with readiness assessment, proceeds to an SBT, and ends with an explicit decision regarding extubation [1,3,4]. Protocols can safely decentralize aspects of weaning from physicians to nurses and respiratory therapists.

The nurse-directed protocol studied by Tonnelier et al. showed shorter weaning times without harm [5], and a Cochrane review of protocolized versus non-protocolized weaning found that structured protocols tend to shorten ventilation and ICU stay while maintaining reintubation rates [10]. These findings support embedding clear algorithms into routine ICU workflows, with multidisciplinary engagement.

The details of SBT implementation matter, but extreme caution is not always better. Perren and colleagues showed that a 30-minute pressure support trial performed as well as a 120-minute trial in predicting extubation success [6].

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Together with earlier work and summaries by Frutos-Vivar and Esteban [4], this suggests that once a patient is stable and passes established criteria, prolonged testing adds little value and can unnecessarily delay liberation.

Automation and closed-loop systems represent an evolution rather than a replacement of traditional protocols. SmartCare/PS reduced time to successful extubation in Lellouche's multicenter trial [7], and subsequent reviews of automated weaning strategies reached similar conclusions, while emphasizing that benefits depend on appropriate patient selection and staff familiarity [11]. Automatic systems embed protocol logic into the ventilator, but clinical oversight remains essential.

Predictors and risk factors extend beyond the lungs. Baptistella et al. documented more than 50 parameters evaluated as predictors of weaning and extubation outcomes, underscoring the multifactorial nature of liberation [11].

Contemporary work shows that frailty, comorbidity burden, and older age independently influence weaning failure and mortality, even when protocol-based strategies are used [13,14] (PubMed). These data argue for integrating standardized weaning tools with a broader assessment of physiologic reserve and goals of care.

Diaphragm-focused tools such as D-RSBI are promising but still early in their evidentiary life cycle. The trial by Mowafy and Abdelgalel found better diagnostic accuracy for D-RSBI compared with conventional RSBI [9], and other series suggest that diaphragm ultrasound can identify patients at risk for weaning failure [11,12]. However, the requirement for ultrasound expertise and the absence of large multicenter validation trials limits immediate generalization.

Available evidence supports a pragmatic framework: daily readiness screening, short SBTs, protocolized titration of support led by nurses and therapists, and selective use of advanced tools (automated systems, diaphragm ultrasound) in patients with difficult or prolonged weaning. Ongoing international cohort studies and newer randomized trials focusing on frailty, comorbidities, and long-term outcomes will further refine how we individualize weaning strategies [12–14].

CONCLUSION

Evidence accumulated over nearly three decades shows that protocolized weaning, centered on daily readiness assessment and structured spontaneous breathing trials, reduces the duration of mechanical ventilation without compromising safety. Nurse- and therapist-led protocols, short standardized SBTs, and selected use of computer-driven systems can further streamline liberation in many intensive care units.

Physiologic indices such as D-RSBI and contemporary data on frailty and comorbidities highlight the need to look beyond ventilator waveforms alone. Future research should focus on integrating these elements into simple, implementable pathways that are adaptable to diverse ICU environments.

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