Chapter

Weaning from Mechanical Ventilation

Liran Statlender and Pierre Singer

Abstract

Weaning off mechanical ventilation (MV) is a process that ultimately ends with a patient's liberation from the ventilator. As extubation failure worsens prognosis, every effort should be made to safely extubate the patient when the clinical condition allows it. There are several methods and techniques to assess whether a patient is ready for weaning. The clinician should choose the proper method for each patient to minimalize the risk of extubation failure. When liberation from MV is not possible, tracheostomy and transferring the patient to a long-term rehabilitation ward may be required. If this is not feasible, palliative care should be considered.

Keywords: weaning, extubation, spontaneous breathing trial (SBT), rapid shallow breathing index (RSBI)

1. Introduction

Weaning from mechanical ventilation (MV) is the process by which a patient is liberated from a ventilator. It begins with a readiness assessment and ends with liberation, usually by extubation. A successful weaning process should discriminate patients who might fail in the extubation and need reintubation from those who might be successful and maintain spontaneous breathing without mechanical support. This is important, as extubation failure and reintubation worsen prognosis and increase risk of mortality, length of stay, length of ventilation, and ventilation-associated events [1].

Ventilation duration affects the weaning process. If a patient was ventilated for a short time (e.g., during a surgical procedure, trauma patient emergency work-up and treatment), it is usually possible to liberate the patient from MV immediately at the end of the procedure without any special difficulties. Of course, patient characteristics matter in these cases (more caution is mandated in a fragile patient than in a young patient). However, longer time of ventilation due to severe respiratory failure or other severe injury or inflammatory process usually mandates a more structured weaning process, which this chapter describes [2, 3].

2. Readiness for weaning

A daily assessment of readiness for extubation should be performed in every ventilated patient. This screening is important to identify patients who might be successfully weaned and to avoid premature extubation in patients who are not ready yet.

The first consideration when weaning a patient from MV is whether the disease that necessitated MV is controlled and in recovery phase. If the disease process is active and not controlled, the patient should not be considered ready for extubation [4].

The second consideration is respiratory function, both oxygenation and ventilation [5]:

1. Oxygenation

   a. $paO_2/FiO_2 > \sim 260$

   b. $FiO_2 < 0.4$

   c. Positive end expiratory pressure (PEEP) < 5 cmH_2O

   If these criteria are not met, it is likely that the patient needs considerable oxygen supplementation.

2. Ventilation

   a. pH > 7.25

A lower pH represents a great load on the respiratory system.

These criteria are considered conservative. For example, early works considered paO_2/FiO_2 of 150 as satisfactory for extubation consideration. Later works suggested a higher cutoff of 260–290 [6–8]. Nevertheless, in specific subgroups of patients, these criteria should be slightly adapted. For example, in patients who suffer interstitial lung disease (or other chronic hypoxic diseases), a $paO_2/FiO_2 > 120$ can be used. In patients who suffers from obstructive lung disease, pH and pCO_2 should be close to the patient's baseline level.

The third consideration is cardiovascular function. Initiation of MV unloads the work of breathing from the patient. Cessation of MV imposes this work on the patient again and adds work to the cardiac output. Moreover, as positive end-expiratory pressure (PEEP) decreases afterload, discontinuation of MV increases afterload, potentially worsening heart failure. Therefore, it is necessary that a patient be hemodynamically stable before weaning (no more than a small and stable rate of vasopressors) [9].

The fourth consideration is neurological status. A patient can be considered ready for extubation if they are alert and cooperative. It is necessary that the patient not be under the effect of IV sedation drugs [4], which might cause respiratory depression (opiates, benzodiazepines, propofol). A small dose of IV sedatives that do not cause respiratory depression (dexmedetomidine, ketamine) is acceptable. Enteral or transdermal analgesia and sedation are possible, as long as the doses are stable and the patient is cooperative.

It is worth emphasizing the importance of patient cooperation. After extubation, the patient will usually have to promote cough, cooperate with respiratory therapy, and might need some support in the form of non-invasive ventilation (NIV) or supplementary oxygen. Failure to cooperate with any of these might lead to re-intubation and thus it is important to achieve the patient's cooperation.

Another issue of neurological status is muscle power, especially the ability to cough [10]. Although specific maneuvers to assess respiratory muscle strength are not superior to current maneuvers to assess weaning probability success, it is important to evaluate the patient's ability to cough, as coughing evacuates secretions and

prevents aspiration. Whenever a patient seems too weak or not able to perform cough mechanics, the risk of aspiration and re-intubation increases.

Other factors to consider are hemoglobin [11] and temperature [12]. Although both are not mandatory and critical to be completely normal before extubation, it is worth confirming that the patient being assessed for weaning is not developing a new problem such as sepsis, bleeding, or hemolysis (any of which might impose further load on the respiratory system and mandate intubation by itself). If so, it might be better to hold off on the weaning process.

2.1 Weaning predictors

When a patient seems ready for extubation, it is possible to perform some measurements as predictors of successful weaning. As no predictor is 100% sensitive and specific, and as some are cumbersome to perform, it is not mandatory to use any of these predictors. Some use weaning predictors in a structured fashion, while others use them only in cases of doubt whether the patient is ready or not [13–15].

The best studied predictor is the Rapid Shallow Breathing Index (RSBI), which is calculated by dividing the tidal volume (in liters) by the respiratory rate (Vt/f). To calculate this predictor, the patient has to breath spontaneously, without any support, for 1 minute, during which the tidal volume and the respiratory rate are measured. Though this measurement is sometimes performed while disconnecting the patient from the ventilator (measurement by external spirometer), it is acceptable to measure RSBI 1 minute after setting the ventilator on zero pressure support and zero PEEP. An RSBI of 105 is considered the cutoff for extubation failure. RSBI >105 has good correlation with extubation failure (negative predictive value 95%), and thus it is advised to delay extubation. However, RSBI <105 does not guarantee successful weaning, as its positive predictive value is about 80%. Interestingly, using automatic tube compensation increases RSBI sensitivity for successful extubation [13, 16, 17].

Other predictors include p/F ratio, dead space measurement, minute ventilation, compliance of respiratory system, work of breathing, P0.1 (inspiratory effort at 0.1 seconds inspirium), maximal inspiratory pressure (MIP), P0.1/MIP, diaphragmatic sonography, tension-time index (TTI), CROP index, CORE index, Weaning Index (WI), and Integrative Weaning Index (IWI). **Table 1** provides more detail about these predictors [13, 18–24]. Although some of these have been shown to better predict successful or unsuccessful extubation than RSBI, there is only slight improvement in prediction, and all these slightly better predictions are more cumbersome to perform than RSBI.

2.2 Spontaneous breathing trial (SBT)

Whether any weaning predictor is used or not, assessing a patient for extubation requires a spontaneous breathing trial. Several techniques are possible, but the basic principle is the same. The spontaneous breathing trial (SBT) is a short period of time in which the patient is breathing spontaneously, with support as minimal as necessary to overcome the endotracheal tube or without support at all. Among the different techniques are using a T-piece device and ventilating using pressure support mode with pressure support (PS) of 0 cmH_2O and PEEP 0 cmH_2O, or PS 0 cmH_2O and PEEP 5 cmH_2O (CPAP), or PS 7–8 cmH_2O and PEEP 5 cmH_2O. There are controversial results from several studies regarding the superiority of specific techniques. Some studies found no difference, while others have shown better success rates with PSV 8 cmH_2O and PEEP 0 cmH_2O compared to T-piece [25]. In any case, FiO_2 during SBT should be 0.4 or lower.

Predictor name	Description	Successful extubation cutoff	Sens	Spec	PPV	NPV
RSBI	RR/Vt	≤105	0.97	0.64	0.78	0.95
Dead space	$\frac{P_{aCO_2} - P_{eCO_2}}{P_{aCO_2}}$	≥0.58*	0.88	0.85	0.62	0.98
Minute ventilation	RR × Vt	≤15	0.78	0.18	0.55	0.38
Dynamic compliance	$\frac{Vt}{PIP - PEEP}$	≥33	0.72	0.50	0.65	0.58
WOB	Vt × P_{TP}	Not defined				
$P_{0.1}$	Pressure at 0.1 sec during maximal inspiratory effort	≤−4.2	0.87	0.61	0.87	0.61
MIP	Maximal pressure during maximal inspiratory effort	≤−25	0.73	0.28	0.75	0.26
$P_{0.1}$/MIP	$\frac{P_{0.1}}{MIP}$	≤−14	0.98	0.61	0.88	0.92
Diaphragm sonography	Sonographic measurement of diaphragm thickness	<24%	0.93	0.58	0.69	0.89
TTI	$\frac{MAP \times T_i}{MIP \times T_{TOT}}$	≥0.18*	1	1	1	1
CROP	$\frac{C_{DYN} \times MIP \times \frac{P_{aO_2}}{P_{AO_2}}}{RR}$	≥13	0.81	0.57	0.71	0.70
CORE	$\frac{C_{DYN} \times \frac{MIP}{P_{0.1}} \times \frac{P_{aO_2}}{P_{AO_2}}}{RR}$	≥8	1	0.95	0.96	1
IWI	$\frac{C_{RS} \times Sat_{O_2}}{RSBI}$	≥25	0.97	0.94	0.99	0.86

**Dead space and TTI predict failed extubation.*
Sens, sensitivity; Spec, specificity; PPV, positive predictive value; NPV, negative predictive value; RSBI, rapid shallow breathing index; RR, respiratory rate; Vt, tidal volume; P_{aCO_2}, arterial partial pressure of carbon dioxide; P_{eCO_2}, end tidal partial pressure of carbon dioxide; PIP, peak inspiratory pressure; PEEP, positive end expiratory pressure; P_{TP}, transthoracic pressure; MIP, maximal inspiratory pressure; TTI, tension time index; MAP, mean airway pressure; Ti, inspirium time; T_{TOT}, total time of inspirium + expirium; Cdyn, dynamic compliance of lung; P_{aO_2}, arterial pressure of oxygen; P_{AO_2}, alverolar pressure of oxygen; RR, respiratory rate.

Table 1.
Weaning predictors and their diagnostic value.

From a historical point of view, SBT was found to shorten weaning time more than previously used methods of weaning such as PSV gradual decrease, IMV gradual decrease, or no SBT at all [4, 26]. In recent years, an automated mode of SBT has been possible due to the development of closed-loop ventilators. These ventilation modes are mainly pressure controlled/pressure supported, but their settings are changed automatically by the ventilator based on oxygen saturation and end tidal monitoring. Upon activation of automated SBT modes, the ventilator decreases support and monitors physiological parameters including heart rate (from saturation pulse), oxygen saturation, respiratory rate, tidal volume, compliance, end tidal CO_2, and RSBI. After completing SBT for a predefined time, the ventilator alerts whether the patient is ready for extubation or not. There is paucity

of data comparing automated SBT to manual SBT, but results seem promising, with a possibility of automated SBT shortening MV duration [27].

When first introduced, the recommendation was to perform SBT for 2 hours. Later studies showed no difference in outcomes with SBT lasting only 30 minutes. When there is a suspicion regarding patient strength, it seems logical to perform longer SBT [28].

As SBT is somewhat challenging for the patient, its endpoint is mainly clinical [5]. To successfully pass the SBT, the patient should remain calm during the test, without any stress signs such as tachycardia, tachypnea, elevated/decreased blood pressure, desaturation, restlessness, feeling uncomfortable, increased effort in breathing, diaphoresis, or new complaints such as chest pain. If any of these occur, the patient has failed the SBT and should remain ventilated. In case of doubt, it is possible to obtain an arterial blood gas (ABG) sample to assess adequacy of oxygenation and ventilation. An ABG sample is also warranted in the case of chronic obstructive pulmonary disease (COPD).

If a patient passes the SBT successfully, extubation should be performed. If a patient fails the SBT, the ventilator should be set to the pre-SBT settings and a workup should be done to determine cause of failure reason and proper treatment. In this case, a daily SBT should take place.

3. Extubation

Once the patient has successfully passed an SBT, extubation should be performed. However, one must pay attention to the patient's ability to remove secretions on their own. Nursing staff should be asked about amounts of secretions and frequency of secretion suctions. Also, patient cough mechanics should be assessed clinically. It is possible that a patient will be screened successfully for extubation and pass an SBT but still suffer from a large amount of secretions or muscle weakness. Suction frequency greater than once every 2 hours is considered unsafe for extubation. Peak expiratory flow during cough <60 L/min is also considered unsafe for extubation. If this is the case, postponing extubation is advised [29].

In select groups of patients who are considered to have risk factors for post-extubation stridor, usually due to laryngeal edema, a cuff leak test is necessary before extubation. This test is not mandatory in all patients, as without any risk factors the leak test is not sensitive nor specific. Risk factors for laryngeal edema include age older than 80 years, female gender, prolonged ventilation (more than 1 week), large-diameter endotracheal tube (more than 8 mm for males and 7 mm for females; smaller diameters are appropriate if the patient is short), CT imaging with endotracheal tube diameter >0.45 than tracheal diameter, Glasgow Coma Scale (GCS) < 8, traumatic intubation, and history of asthma. Any one of these endanger the patient for stridor and therefore mandate performing a cuff leak test. The cuff leak test is performed by deflating the endotracheal tube cuff and measuring the difference between the inspired tidal volume to the expired tidal volume (during volume-controlled ventilation). Generally, when a patient suffers from laryngeal edema, there will be small air leak, if any. Usual cutoffs that support this diagnosis are leak of <110–130 ml or <12–24% of the inhaled tidal volume. If the cuff leak test is positive (i.e., the patient suffers from laryngeal edema), a course of steroids should be given (methylprednisolone 20 mg every 6 hours) before next evaluation [30].

When the patient is ready for extubation, all necessary arrangements should be made to perform the procedure safely. The physician who performs the extubation

must keep in mind that despite taking all precautions, the patient might fail immediately and be prepared for reintubation. This is the main theme of the extubation.

Once the decision to extubate the patient is made, FiO_2 of the ventilator should be set to 1. This is the preoxygenation for possible reintubation. All the equipment needed to intubate must be within grasp, including sedation drugs, laryngoscope, endotracheal tube (usually half the size of the current tube), suction tube, and resuscitation cart. If prior intubation of the patient was difficult, then the method that was finally used should be available. Before extubation, a suction is performed within the tube and oral cavity to prevent aspiration. The patient is placed in the upright position and a short explanation about the procedure is given. Extubation itself is performed either with a bag valve mask (e.g., Ambu bag) without one. With an Ambu bag the cuff is deflated, and small positive pressure is constantly applied with the bag while pulling the tube out. Without a bag, the patient is asked to take a deep breath and hold. In that time the cuff is deflated, and the tube is quickly removed. The purpose of both techniques is to set exhalation by the patient as the first movement without the tube to decrease the chance of aspiration.

3.1 Post extubation management

Usually, immediately after extubation the patient is supported by oxygen. Respiratory therapies are advised shortly after the extubation to support secretion removal. Closed monitoring for any sign of respiratory distress is mandatory to allow intervention and reintubation, if necessary, as soon as possible after respiratory distress appears.

About 85% of patients are at low risk of reintubation. Usually, these patients are managed with low-flow oxygen (nasal prongs, simple mask). Occasionally, a patient will be more comfortable with a high-flow nasal canula (HFNC), even without overt hypoxemia. Patients in this group should be monitored closely for 12–24 hours, and if there are no alarming events, they can be discharged from the ICU afterwards (considering no other active ICU problems) [2, 31].

About 15% of patients are at high risk of reintubation within 48 hours of extubation. These patients should be closely monitored and treated accordingly to avoid reintubation. High-risk patients are considered those whose cough is ineffective, who need secretion suction at a frequency greater than one suction every 2 hours, who are in positive fluid balance, who were intubated because of pneumonia. Who are not fully conscious, and who suffer from congestive heart failure (CHF) or COPD. Treatment should be focused with the etiology of deterioration (frequent secretion suction, diuretics, etc.) [1].

Applying HFNC or NIV to these patients seems beneficial in some instances, but this has not been proven. Applying NIV to all extubated patients was not found efficient in all studies performed. In select patients, immediate use of HFNC or NIV might be beneficial, especially in those patients who suffer from COPD or CHF. Both of these patient populations have specific indications for PEEP and therefore have better outcomes when extubated directly to bilevel positive airway pressure (BiPAP). HFNC was found to be non-inferior to NIV, in that instance [32, 33].

When a patient develops respiratory failure after extubation, applying NIV or HFNC might be harmful, as usually it does not prevent reintubation, but rather only postpones it. As such, when the patient finally goes to reintubation, their muscle fatigue is greater than before the NIV/HFNC challenge [4, 34]. Therefore, when a patient starts to deteriorate after extubation, careful monitoring should be performed. If an etiology of deterioration is evident, it must be treated aggressively (suction of secretions, CHF treatment, etc.). If no such reason is apparent, or if treatment response is not sufficient, it is better to reintubate the patient than to challenge with NIV/HFNC.

Reintubation is a bad prognostic factor. Usually, reintubated patients are hospitalized for a longer time (both in ICU and in hospital), suffer from more infections, and have higher mortality rates [1].

4. Management of SBT failure and the difficult-to-wean patient

Approximately 60% of patients manage to pass their first SBT and are extubated successfully. These patients are classified as having simple extubation. About 40% of patients do not pass their first SBT and thus will be classified (initially) as difficult to wean (**Table 2**). These patients should undergo workup to determine why SBT failure occurred. While determining reasons for failure, daily SBT should take place. Most patients who are difficult to wean will require up to three SBTs or 7 days to pass an SBT [2].

Several pathophysiological processes might cause SBT failure. These are classified according to the main system that compromises the patient.

1. Respiratory/ventilatory: hypoxemia, V/Q mismatch, sepsis (excessive CO_2 production), increased airway resistance (COPD/asthma), dynamic hyperinflation, increased secretions, atelectasis, pleural effusion, pneumothorax, ventilator circuit malfunction

2. Cardiac: CHF deterioration, fluid overload

3. Neurological: decreased respiratory drive, oversedation, delirium, anxiety

4. Muscular: respiratory muscle weakness, electrolyte disorders (hypophosphatemia, hypomagnesemia, hypocalcemia, hypokalemia), neuropathy or myopathy, underfeeding, protein catabolism, hypothyroidism

Usually, a careful patient examination involving history review, physical examination, ventilator graph analysis, basic laboratory examination, and imaging studies might reveal the reason and aid treatment.

During the time between SBTs the patient should be ventilated in settings that will maintain oxygenation and ventilation targets, in accordance with lung protective ventilation principles. Usually, PSV mode would apply. However, the patient must be comfortable with PSV settings. In addition, to allow respiratory muscles to rest, some patients may require mandatory ventilation.

Once the process that is suspected to have failed the previous SBT is treated, the patient can undergo another SBT. Usually, this SBT should be longer than the previous one, about 2 hours. The SBT technique should be the same as the previous attempt. However, if CHF is suspected as the reason for SBT failure, it might be better to perform an SBT with a T-piece. This will allow to examine whether the patient can tolerate absence of PEEP.

If the patient successfully passes the SBT, an extubation should be performed. However, if the patient fails, the SBT should be halted at the first signs of failure to decrease fatigue of respiratory muscles.

4.1 Prolonged weaning/prolonged mechanical ventilation

Patients who are not able to pass an SBT in three consecutive attempts or who take more than a week to pass are considered to be going through prolonged weaning. Although they represent the minority (about 10%), these patients are at increased risk of death and are likely to need tracheostomy [3].

Group	Description	Proportion of patients (%)
Simple weaning	Successful extubation at the first attempt of weaning process	85
Difficult weaning	Failure of extubation or SBT at the first attempt, but successful extubation with two further attempts and within 1 week	10–15
Prolonged weaning	At least three failures of extubation or SBTs or duration of weaning process is longer than a week	5

Adapted from Boles et al. [2]

Table 2.
Weaning process classification.

Assuming the acute illness has already recovered, and those pathologies that might cause SBT failure were also treated, the most prominent reason for prolonged MV is imbalance between respiratory system load and capacitance. In other words, patients who need prolonged MV are patients whose respiratory systems cannot meet the physiological demands of the body, whether because of lung pathology (abnormal lung mechanics), respiratory muscle weakness, or neurological dysfunction [31].

Medically, a patient who needs prolonged MV should undergo tracheostomy. This is done to improve patient communication, decrease sedation, ease nursing treatment, and allow for transfer to a long-term weaning facility. With coordination of physicians, nurses, physical therapists, clinical dietitians, and social workers, long-term weaning facilities focus on weaning and rehabilitation. As reasons of prolonged MV are multifactorial, there is no accepted strategy to liberate a patient from the ventilator, and a tailored approach to each patient is feasible.

Outcomes of long-term rehabilitation wards are as follows:

- About 55% of patients are successfully weaned. Average time to wean is approximately 30 days (at the rehabilitation ward). Approximately 40% of these patients survive 1 year.

- About 15% of patients remain ventilator dependent (inability to wean within 3 months). One-year survival in this group is about 20%.

- About 30% of patients die during admission.

One-year survival is variable among different studies, in the range of 25–75%. Most likely, this represents variability in patients' baseline characteristics [35].

Upon diagnosing a patient as one who needs prolonged MV, it is important to discuss this with the patient (or the patient's next of kin/primary caregiver/legal guardian) and explain the chances of remaining ventilator dependent and possible quality of life. If patient expectations are not possible to meet, it seems appropriate to discuss the option of palliative care.

5. Conclusion

Weaning is the process of liberating a patient from MV. Whenever a patient is ventilated for more than 24 hours, the weaning process should be a structured process. **Figure 1** presents the weaning process as performed in our unit. This allows for patient safety and avoids unnecessary extubation failures, which worsen prognosis.

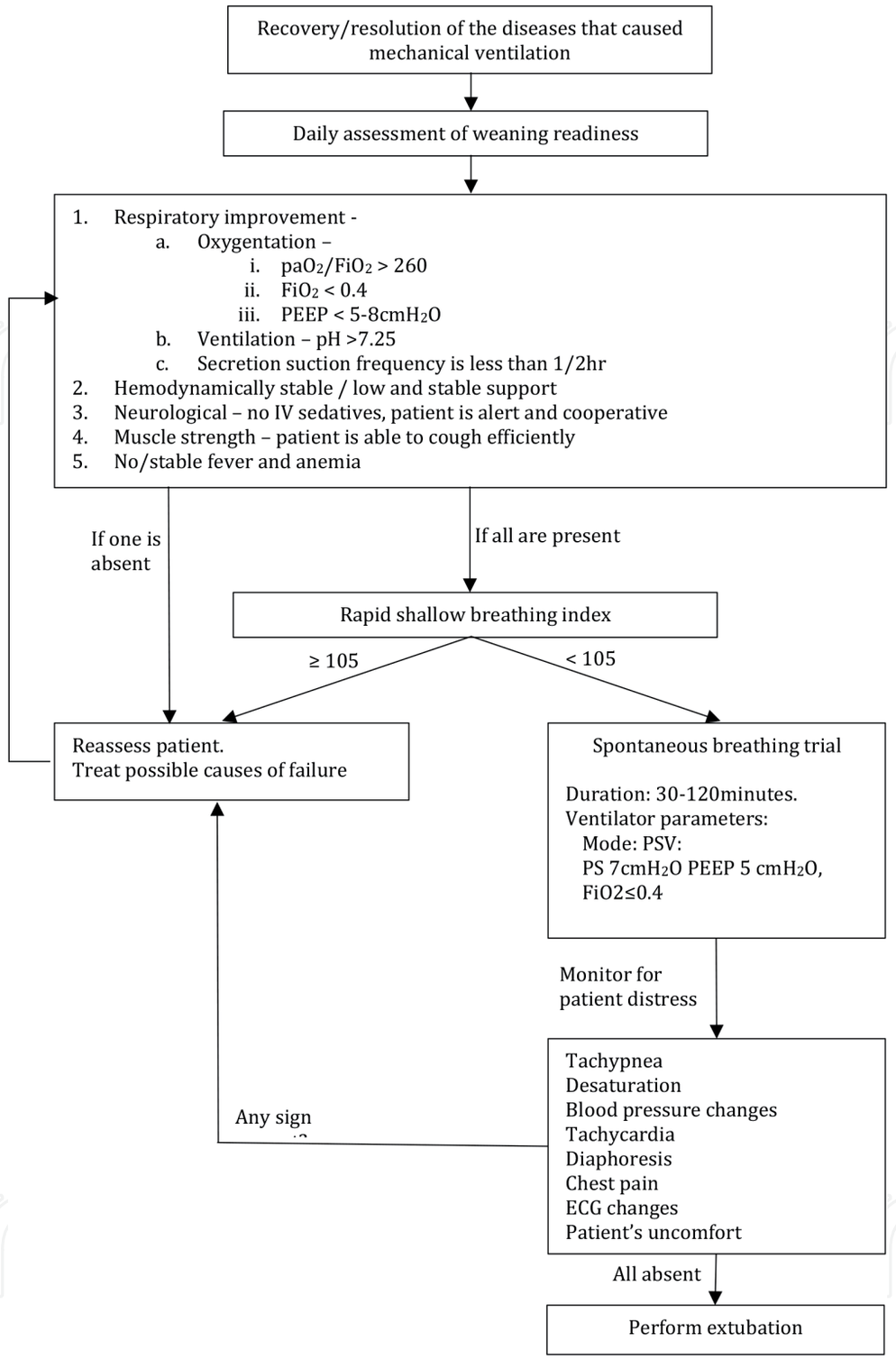

Figure 1.
Suggested flow chart of weaning process.

In most cases, the patient will be extubated without complications. In a minority of cases, special attention should be given to pathological processes that might endanger the patient to extubation failure. In severe cases, weaning will be a long process performed in dedicated ward.

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Author details

Liran Statlender* and Pierre Singer
Rabin Medical Center, Petach Tikwa, Israel

*Address all correspondence to: liranst1@clalit.org.il

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