Long-Term Home Ventilation in Children: Advances and Perspectives

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Fabrizio Racca, Cesare Gregoretti, Elena Capello, Cristina Bella, Ida Salvo, Edoardo Calderini and Marco Ranieri

7.1 Introduction

Long-term mechanical ventilation (LTMV) has been defined as the need for mechanical ventilation delivered via tracheotomy (invasive mechanical ventilation) or noninvasive interfaces (noninvasive ventilation, NIV), including continuous positive airway pressure (CPAP), for at least 3 months after its commencement, for a minimum amount of 6 h per day, in medically stable conditions [1,2]. A recent Italian study showed that all LTMV users received invasive or noninvasive positive pressure ventilation (NPPV) and only 1.5% of children were also managed with other ventilatory assistance modes (i.e., 1% with glossopharyngeal breathing and 0.5% with phrenic nerve stimulation) [1].

Over the past 20 years, LTMV in the pediatric population has rapidly expanded [1–7]. This has been attributed to a number of factors: (1) continuous advances in neonatal and pediatric intensive care are likely to result in a greater number of children with critical chronic conditions, who survive and are discharged home, but who require long-term technological support [4]; (2) a growing population of children exists who have chronic respiratory failure (CRF) due to conditions such as neuromuscular disorders (NMDs), obstructive sleep apnea, or craniofacial abnormalities; (3) LTMV for children with NMDs and chest wall disorders is an established supportive therapy that reduces morbidity and mortality [8–11]; and (4) manufacturing development (i.e., mechanical ventilators and noninvasive interfaces) has made NIV a practical option even for very young children [4].

It is now accepted practice that the home environment is preferable to the hospital setting once the decision to institute LTMV in an infant or child with a stable or progressive disorder of the respiratory system has been taken [12]. In fact, LTMV at home offers the best option for the child's psychosocial development, social

F. Racca (✉)
Pediatric Anesthesiology and Intensive Care Unit,
SS. Antonio Biagio e Cesare Arrigo Hospital, Alessandria, Italy
e-mail: fabrizio.racca@gmail.com

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integration, and quality of life. Moreover, the direct cost of home care is usually lower than that of hospital care [12]. As matter of fact, several surveys have shown that the majority of children on LTMV are successfully discharged home [1–3,7].

The aim of this chapter is to discuss some of the issues and problems arising from home mechanical ventilation in children.

7.2 The Rationale for the Use of Long-Term Mechanical Ventilation

The ability to sustain spontaneous breathing can be viewed as a balance between neurological mechanisms controlling ventilation and respiratory muscles power on the one hand, and the respiratory load determined by lung, thoracic, and airway mechanics on the other. In healthy children, the central respiratory drive and respiratory muscle power exceed the respiratory load; thus, they are able to sustain adequate spontaneous ventilation. Significant dysfunction of any of these three components of the respiratory system may impair the ability to generate spontaneously efficacious breaths. If respiratory load is too high and/or respiratory muscle power or the central respiratory drive is too low, ventilation may be insufficient, resulting in alveolar hypoventilation and hypercapnic CRF [12].

Several factors make very young children more susceptible than adults to develop respiratory failure [12,13]. Because of pulmonary and chest wall mechanics (i.e., a relatively stiff lung and a very compliant chest wall), respiratory load is increased. The compliant chest wall also impedes the ability to generate adequate tidal volumes (TVs). The mechanics of the respiratory system are further hampered by high-flow resistance of the nasal airway and small airways. Reduced respiratory muscle strength and endurance increase a child's susceptibility to fatigue. In addition, in young children the neurological control of breathing is an intrinsically unstable system, which predisposes to apnea and hypoventilation. Finally, the formation of alveoli is essentially complete by 18 months and the metabolic rate in very young children is approximately twice that of adults, thus increasing the risk of hypoxemia. If the respiratory imbalance leading to hypercapnic CRF cannot be corrected with medical treatment, ventilator support may be indicated.

Infants and children may require LTMV due to one or more of three categories of respiratory system dysfunction: (1) increased respiratory load (due to intrinsic pulmonary disorders or skeletal deformities); (2) respiratory muscle weakness (due to neuromuscular diseases or spinal cord injury); or (3) failure of the neurological control of ventilation (central hypoventilation syndrome) [12] (see Table 7.1). The majority of children on LTMV have NMDs [1–3,6,7] and the most represented NMDs are spinal muscular atrophy [1] and congenital myopathy [7].

The decision to initiate LTMV in a pediatric patient may be undertaken electively or non-electively [12]. In the past, most decisions to begin LTMV were made *non-electively*. LTMV was started as a result of weaning failure after the institution of mechanical ventilation in the acute setting. More recently, the decision to

Table 7.1 Causes of chronic respiratory insufficiency in pediatric patients

1. Increased respiratory load	1.1 Chronic pulmonary disorders	1.1.1 Upper airway obstruction: obstructive sleep apnea; craniofacial syndromes; airway malacia; vocal cord paralysis; Prader-Willi syndrome; obesity syndromes; Down syndrome; achondroplasia 1.1.2 Chronic lung disease: bronchopulmonary dysplasia; lung hypoplasia; cystic fibrosis
	1.2 Chest wall disorders	Severe kyphoscoliosis; thoracic dystrophy; other thoracic wall deformities
2. Ventilatory muscle weakness	2.1 Neuromuscular disorders	2.1.1 Motoneuron diseases: spinal muscular atrophy (SMA); SMA with respiratory distress 2.1.2 Peripheral neuropathies: phrenic nerve paralysis; Guillain-Barré syndrome; chronic inflammatory demyelinating polyneuropathy 2.1.3 Neuromuscular junction diseases: myasthenia gravis (MG); congenital autoimmune MG; congenital myasthenias 2.1.4 Muscle diseases: *Progressive muscular dystrophies*: Duchenne muscular dystrophy; myotonic dystrophy *Congenital muscular dystrophies*: Ullrich congenital muscular dystrophy (CMD); Bethlem myopathy; Emery-Dreifuss dystrophy; merosin-deficient CMD alpha-dystroglycanopathies *Congenital myopathies*: central core disease; nemaline rod myopathies; centronuclear/myotubular myopathy; fiber-type disproportion myopathy; myofibrillar myopathies *Metabolic myopathies*: mitochondrial encephalomyopathies; glycogen storage disorders (GSDs; i.e.; GSD type II or Pompe disease); lipid storage myopathies
	2.2 Spinal cord injury (above C3):	Traumatic spinal cord injury; tumor; surgery
	2.3 Encephalopathy	Birth injury; cerebral palsy
3. Ventilation control failure	3.1 Congenital central hypoventilation:	– Congenital central hypoventilation syndrome (Ondine's curse) – Late-onset central hypoventilation syndrome – Rapid-onset obesity with hypothalamic dysfunction; hypoventilation, and autonomic dysregulation
	3.2 Acquired central hypoventilation	Trauma; tumor; surgery; hemorrhage; radiation; myelomeningocele; Arnold-Chiari type II

CMD congenital muscular dystrophy, *GSD* glycogen storage disorder, *MG* myastenia gravis, *SMA* spinal muscular atrophy

start LTMV is increasingly being made *electively* to preserve physiological function. In this case, LTMV is aimed at: (1) unloading the respiratory muscles; (2) decrease hypercapnia during wakefulness; (3) reduce fatigue and improve respiratory muscle performance; (4) preserve normal pulmonary mechanics; (5) improve nutritional status; (6) avoid chest wall distortion; (7) preserve normal growth; (8)

increase sleep quality; (9) facilitate airway clearance during physiotherapy; (10) reduce hospitalizations and intensive care unit care; and (11) improve quality of life [12,13]. Finally, in patients with NMDs and chest wall disorders, LTMV has been shown to reduce morbidity and mortality [8–11].

When the decision to initiate LTMV is taken electively, ventilatory support is usually applied first during the night. This is due to several factors: (1) an increase in upper airway resistance due to a decrease of tonic activity of the upper airway muscles occurs during rapid eye movement (REM) sleep; (2) a reduction in respiratory pump performance during REM sleep due to the reduced activity of intercostal muscles coupled with a preserved activity of the diaphragm; (3) a fall in functional residual capacity leading to an increase in ventilation-perfusion mismatch; and (4) a modification of the central drive due to an alteration of chemoreceptor sensitivity during sleep.

LTMV nocturnal beneficial effects may be extended, after prolonged use, during diurnal spontaneous breathing. These effects may be due to an increase in respiratory drive caused by a reduction in cerebrospinal fluid bicarbonate concentration which resets the ventilatory response to CO_2. Moreover, an improvement in sleep quality influences respiratory muscle endurance [14].

7.3 Criteria for Home Discharge

Once a child, who started LTMV non-electively, has become clinically stable both in terms of underlying disease symptoms and ventilator settings, they have become a candidate for LTMV given at home. Indeed, with proper patient selection, home care is safe and optimizes the patient's quality of life, rehabilitative potential, and reintegration with the family [12].

However, the child who is going to be discharged to home care should present the following conditions: (1) respiratory system stability; (2) ventilator requirement stability; (3) stability of other medical conditions for a relatively sustained period of time (1–2 weeks); and finally (4), it must be considered if the current level of care can be continued at home [12].

Respiratory system stability means that children should meet the following stability criteria:

1. The child should have safe and secure airways (i.e., either tracheostomy with a sufficient mature stoma to allow tube changes, or stabilized on regimen of NIV with minimal risk for aspiration).
2. The child should be able to clear secretions, either spontaneously or with assistance (i.e., manually or mechanically assisted coughing).
3. The child should not have episodic severe dyspnea nor sustained episodes of moderate dyspnea.
4. The child should have stable airway resistance and lung compliance.
5. Oxygenation should be stable including during suctioning and tracheostomy repositioning.

Ventilator requirement stability means that:

1. The child should have stable ventilator settings on the ventilator in use and defined type of respiratory circuits;
2. The child should have stable fraction of inspired oxygen (FiO_2) ≤ 0.4 with positive end-expiratory pressure (PEEP) ≤ 5 cm H_2O (unless on higher PEEP for obstructive sleep apnea);
3. The child, ideally, should be able to do some ventilator-free breathing.

Stability of other medical conditions means that all other medical problems should be controlled and that there are no major diagnostic considerations or changes in therapeutic interventions requiring hospitalization within 1 month (i.e., treatment plan for all medical conditions is in place, will not require frequent changes, and can be implemented at home). Furthermore, an adequate nutrition program is in place, preferably through the enteral route.

Finally, to continue at home the current level of care, the child should have: (1) stable home and family setting; (2) a home environment prepared in advance to accommodate their needs; and (3) caregivers identified and trained to provide the necessary care prior to discharge.

7.4 When to Start Elective Long-Term Mechanical Ventilation

Elective LTMV is started when spontaneous respiratory muscle efforts are unable to sustain adequate alveolar ventilation. If reversible deteriorating factors (i.e., respiratory infection, heart failure, severe electrolyte disturbance) have been treated successfully, indications for elective LTMV include symptomatic or nonsymptomatic daytime hypercapnia, symptomatic or nonsymptomatic nocturnal hypoventilation, failure to thrive, recurrent chest infections, paradoxical breathing, and chest wall deformity [8,9,15–18]. The criteria for selecting children with CRF to receive elective LTMV are listed in Table 7.2.

In children with spinal muscular atrophy (SMA) type 1, care without ventilation support is an option if the burden of treatment outweighs the benefits. If supportive ventilation is chosen by the family, NIV is recommended. In fact, for these patients, tracheotomy is controversial and an ethical dilemma. On the other hand, NIV can be used as a palliative to facilitate discharge from hospital to home and to reduce the work of breathing [8,17].

Respiratory status in patients with CRF is assessed primarily with *pulmonary function tests* [8,9,15]. Spirometry in sitting and supine positions is of particular importance as a difference greater than 20% between the sitting and supine vital capacity is indicative of diaphragmatic weakness and suggests a higher risk of nocturnal hypoventilation. Moreover, a sitting vital capacity that is lower than 40% of the predicted value is indicative of nocturnal hypoventilation [15]. An oronasal mask allows children with facial weakness to achieve a reliable value for vital capacity. For patients unable to perform standard spirometry because of young age or developmental delay, a crying vital capacity can be obtained by placing a

Table 7.2 Criteria for the selection of children with CRF for long-term mechanical ventilation

Nocturnal ventilation is indicated in patients who have any of the following:
- significant daytime CO_2 retention ($PaCO_2$ > 45–50 mmHg while awake);
- signs or symptoms of hypoventilation (patients with FVC < 30% predicted are at especially high risk);
- significant nocturnal hypoventilation ($PtcCO_2$ ≥ 50 mmHg for > 10% of nocturnal recording time or $PtcCO_2$ ≥ 50 mmHg for at least 5 continuous min) or significant oxygen desaturation (SpO_2 was < 90% for > 10% of nocturnal recording time or SpO_2 was ≤ 90% for at least 5 continuous min, or four or more episodes of SpO_2 < 92%, or drops in SpO_2 of at least 4% per h of sleep) or an apnea-hypopnea index > 10 per h on polysomnography;
- failure to thrive;
- recurrent chest infections (> 3 a year);
- paradoxical breathing and chest wall deformity (above all in children with SMA type 1).

In patients already using nocturnally assisted ventilation, daytime ventilation is indicated for:
- self-extension of nocturnal ventilation into waking hours;
- abnormal swallowing due to dyspnea, which is relieved by ventilatory assistance;
- inability to speak a full sentence without breathlessness;
- symptoms of hypoventilation with significant daytime CO_2 retention ($PaCO_2$ > 45–50 mmHg while awake).

CRF chronic respiratory failure, *FVC* forced vital capacity, *$PaCO_2$* partial pressure of oxygen (in the blood), *$PtcCO_2$* transcutaneous CO_2, *SpO_2* oxygen saturation, *SMA* spinal muscular atrophy

tightly fitting mask on the nose and mouth with a spirometer in line [15]. Maximal inspiratory pressure and maximal expiratory pressure are additional measures of pulmonary function. Values < 60 cm H_2O suggest respiratory impairment.

Arterial or capillary blood gases assess hypercapnic respiratory failure (i.e., a partial pressure of CO_2, $PaCO_2$) in the blood > 45 mmHg). Sleep studies are used to evaluate nocturnal respiratory compromise [8, 15]. In particular, polysomnograms can detect or confirm sleep-disordered breathing and should include end-tidal CO_2 monitoring or transcutaneous CO_2 monitoring. When polysomnography is not available, an alternative is to use a 4-channel sleep study that records heart rate, nasal airflow, and chest wall movements during sleep. In cases where neither polysomnography nor a 4-channel study is available, overnight pulse oximetry with continuous CO_2 monitoring may provide useful information about nighttime gas exchange [8].

Furthermore, a proactive approach should be taken to recognize the "early symptoms of pulmonary problems" prior to the onset of chronic respiratory compromise. Early symptoms can be subtle and may include disturbed sleep, increased need to turn at night, waking in the morning feeling tired, disturbed mood, irritability and poor concentration during the day, morning headaches, nausea, fear of going to sleep, and nightmares. These symptoms are typically related to nighttime hypercapnia and hypoxemia. However, the onset of hypoventilation may be insidious and patients may be clinically asymptomatic [8].

Repeated chest infections, accessory muscle use, tachypnea, presence of paradoxical breathing, swallowing difficulties, and poor weight gain or weight loss can also be signs of pulmonary impairment [8,15].

Additional screening tests should include a baseline chest X-ray to provide an initial reference point and for comparison during respiratory deterioration or unexplained hypoxemia due to unsuspected atelectasis. Moreover, formal evaluation of swallowing should be considered in patients with NMDs if clinically indicated or in cases of an acute unexplained respiratory deterioration and recurring pneumonia [8]. Finally, children with NMDs should be evaluated for the presence and severity of scoliosis [8].

7.5 How to Deliver Long-Term Mechanical Ventilation

LTMV can be delivered in the home setting as noninvasive CPAP or as intermittent positive pressure ventilation (IPPV) [12].

CPAP applies a constant distending airway pressure throughout the entire respiratory cycle, while the patient is breathing spontaneously. CPAP exerts its effects in patients with CRF by: (1) splinting the upper airway; (2) stabilizing the chest wall; (3) counterbalancing the intrinsic PEEP; (4) recruiting lung volume and maintaining inflated collapsed alveoli; and (5) reducing the cardiac afterload.

Invasive or noninvasive IPPV assists ventilation during inspiration by delivering pressurized gas to the airways, increasing transpulmonary pressure, and inflating the lungs. Exhalation occurs by means of elastic recoil of the lungs with or without active force exerted by the expiratory muscles. IPPV exerts its effects in patients with CRF by: (1) increasing alveolar ventilation; (2) unloading respiratory muscles; and (3) relieving the patient's dyspnea.

During IPPV, ventilators can deliver a positive pressure breath regardless of the patient's inspiratory drive (total ventilator-controlled mechanical support: "controlled mechanical ventilation") or in synchrony with the patient's effort (partial patient-controlled mechanical support modes: "assisted mechanical ventilation"). In the "assisted modes", the patient's spontaneous inspiratory effort triggers the ventilator to provide a volume (volume-targeted ventilatory modes) or pressure (pressure-targeted ventilatory modes).

Volume-targeted ventilation (VTV) is characterized by the delivery of a predetermined TV. The main advantage of this mode is that a minimal volume is guaranteed. On the other hand, pressure being the dependent variable, high inspiratory airway pressures may cause discomfort and poor tolerability [19]. Moreover, this mode is less efficient in compensating for air leaks than pressure-targeted ventilation.

Differently from VTV, during pressure-targeted ventilation the independent variable is pressure, while flow is the dependent variable. As a consequence, TV is not predetermined, depending on the level of pressure, patient's inspiratory effort, and the mechanical properties of the respiratory system (i.e., resistance and compliance). Pressure-targeted ventilation includes assist-control pressure-targeted ventilation and pressure support ventilation (PSV). During assist-control pressure-targeted ventilation each breath may be triggered by the patient's effort and terminated at a given time. Patients control the respiratory rate, but the breath is always

time-cycled. The ventilator set-up always asks for a backup rate and for ventilator inspiratory time (usually 33% of the patient's duty cycle). During PSV each breath is triggered by the patient's effort and terminated at a given preset or adjustable threshold of the patient's inspiratory flow decay (i.e., the termination criteria). Therefore, in this mode patients can control both the respiratory rate and the inspiratory duration [20]. Even if during genuine PSV there are no mandatory breaths present, home ventilators frequently have a PSV mode incorporating a backup rate to prevent episodes of apnea.

New turbine-driven ventilators can be set on VTV or pressure-targeted ventilation, and integrate new options such as "pressure-targeted ventilation with closed-loop control", which guarantees a minimal TV. The principle of this "volume guarantee" module is based on the automatic detection of the TV by the ventilator. When the TV falls below a fixed threshold, the ventilator increases the inspiratory positive pressure or inspiratory flow and eventually the inspiratory time until the delivered TV is reached. After the resolution of a pathological condition (i.e., an increase in airway resistance), the ventilator should be able to return to its baseline settings while preserving the patient's ventilator synchrony.

The optimal mode for LTMV has not been established. Therefore, the choice between ventilatory modes is determined by the type of the underlying disease and the habits of the prescriber. However, the majority of patients with tracheostomy are managed with VTV or pressure-targeted ventilation with "volume guarantee," reflecting the common practice of using ventilation modalities with a guaranteed TV even in case of changes in resistance (i.e., secretions, tube plugging, and so on) [1]. In addition, VTV may be required for patients with advanced restrictive disease, such as NMD patients, in whom daytime mouthpiece ventilation may be necessary. Indeed, mouthpiece ventilation can only be performed with a volume-targeted mode. Finally, VTV may be preferred in patients with NMDs because of their ability to "stack" breaths to assist cough. On the other hand, children with chronic lung disease noninvasively ventilated are preferentially assisted with pressure-targeted ventilation, which may compensate for air leaks, by varying the inspiratory flow, and which enhances patient comfort resulting in higher treatment "compliance" [1]. Finally, CPAP is almost exclusively applied as a first-line therapy in patients with upper airway obstruction [1].

Once the ventilator mode is chosen, the optimal setting for LTMV has to be established. In general, mechanical ventilation settings are individualized to achieve adequate inspiratory chest wall expansion and air entry, and the normalization of oxygen saturation (SpO_2) and end-tidal CO_2 or transcutaneous CO_2 measurements. For children without significant pulmonary disease, ventilators are adjusted to provide an end-tidal CO_2 partial pressure (pCO_2) of 30–35 mmHg and $SpO_2 > 95\%$ [12]. In these patients, the partial pressure of CO_2 in the blood ($PaCO_2$) should be adjusted slightly lower than the physiological $PaCO_2$ (i.e., 30–35 mmHg) to provide a margin of safety and eliminate subjective feelings of dyspnea [12]. For children with pulmonary disease, these low pCO_2 values may not be achievable, and supplemental oxygen may be required, in addition to mechanical ventilation, to achieve adequate oxygenation [12].

The level of positive pressure required to eliminate obstructive apneas or hypopneas and normalize ventilation and nighttime SpO_2 must be determined in the sleep laboratory or with careful bedside monitoring and observation.

Patient-ventilator asynchrony may become a major issue during the "assisted modes" leading to mechanical ventilation failure. Essouri and colleagues found that CPAP and NIV were associated with a significant and comparable decrease in respiratory effort in infants with upper airway obstruction. However, NIV ventilation was associated with patient-ventilator asynchrony [21].

At home, ventilator settings cannot be changed frequently to maintain perfect blood gas values. Thus, settings should not be changed in response to minor variations in blood gas values, but only to correct persistent trends or major abnormalities.

Once the child is at home, serial evaluation and adjustment of LTMV are necessary, as the child grows and as patient's requirements change with time. Consequently, ventilator settings must be evaluated to assure adequate gas exchange (pulse oximetry, capnography, transcutaneous pO_2 and pCO_2) on a regular basis. Generally, these evaluations should be performed more frequently in infants and small children with rapid growth, and less frequently in older children with slower growth. In preschool children, ventilator settings should be checked every 4–8 months. After the fourth year of life, ventilator settings should be checked every 6–12 months [12]. Furthermore, following any change in the respiratory system (such as severe infection or hospitalization), ventilator settings should be checked and readjusted.

7.6 Characteristics of Home Ventilators

Some home ventilators are pressure-targeted, others volume-targeted, and new turbine-driven ventilators contains both modes and can be set on different modalities, such as CPAP and PSV, as well as VTV and assist pressure control ventilation (APCV), with or without PEEP. Furthermore, some home ventilators are able to deliver "intentional leak" ventilation by using a single circuit with manufactured leaks [such as CPAP or bilevel positive airway pressure (BiPAP), others can deliver "non-leak" ventilation by using a single circuit with an expiratory valve or a double circuit, and several new ventilators contain both these modalities.

"Intentional leak" ventilation is very effective in compensating for additional leaks. This ability is very important in the case of NIV. Furthermore, using NIV, the choice between leak and non-leak ventilation is also determined by the type of underlying disease. For patients with upper airway obstruction, who need a continuous positive airway pressure to maintain the patency of the upper airway, "intentional leak" ventilation with CPAP or BiPAP is simple and perfectly appropriate [21,22]. However, BiPAP devices do not generally perform intermittent positive ventilation as well as classical ventilators, especially in term of the maximal delivered pressure above PEEP [23]. Consequently, patients with NMDs or lung disease are often ventilated with non-leak ventilation to ensure adequate alveolar ventilation.

Leak ventilation is also sometime used in tracheotomized patients with plain tracheostomy tubes and who receive assisted ventilation on an intermittent basis; however, "intentional leak" ventilation should not be used for tracheotomized patients who are entirely ventilator-dependent. Non-leak ventilation is usually preferred in those cases [1,12].

The quality of the inspiratory triggers may limit the performance of ventilators. The patient's inspiratory effort may be too low, reducing the ability of the ventilator to detect the onset of inspiration. With a classical pressure trigger, a closed system is mandatory to facilitate the generation of a differential pressure. With an open system (i.e., leak ventilation), triggers based on a flow signal are better than pressure triggers. Indeed, in case of a flow trigger, the ventilator should be able to detect very low flows, especially in young children, who have small TVs. Nevertheless, because of the lack of information disclosed by the manufacturers concerning the principle and algorithms used for the inspiratory trigger, it is difficult to understand why one ventilator seems to exhibit a better trigger than another.

Even though home ventilators are becoming increasingly sophisticated, children with respiratory failure, especially the youngest ones, may develop extreme breathing patterns and low inspiratory effort, which may represent a challenge for a ventilator [21]. The lack of detection of the patient's inspiratory and expiratory effort by the majority of ventilators in infants and young children has been previously observed in the study by Essouri and colleagues [21]. Consequently, home ventilators may not be able to adequately synchronize with the respiratory effort in children [24, 25], and leak compensation may be insufficient for young children. This is explained by the fact that most ventilators have not been specifically developed for pediatric patients. Moreover, most of the home care ventilators are not designed to operate within certain limits (e.g., TV between 50 and 100 mL). Thus, these ventilators may not be suitable for very small infants (< 6 kg) [12].

However, in clinical practice, the clinician has to deal with the available devices. A recent French bench study evaluated the performance of 17 ventilators available for home ventilation with the most common pediatric profiles, namely NMD, upper airway obstruction, and cystic fibrosis [23]. This study confirmed the limitations of the ventilators currently available for home ventilation in children. Indeed, it showed that: (1) no ventilator was perfect and able to adequately ventilate the different patient profiles; (2) ventilator performance was very heterogeneous and depended on the type of trigger and circuit and, most importantly, on the characteristics of the patient; and (3) the sensitivity of the inspiratory triggers of most of the ventilators was insufficient for infants [23]. In particular, the study showed that a total of 12 ventilators had a trigger delay < 150 ms for fewer than two profiles and only one ventilator for three profiles. In all other cases, the trigger was "inappropriate", meaning that ineffective efforts (i.e., the patient was trying to trigger – indicated by an abrupt airway pressure drop simultaneous to a flow decrease–, but the ventilator did not deliver a breath) or auto-triggering (i.e., the ventilator is delivering a mechanical breath without a prior airway pressure de-

crease, indicating that the ventilator delivers a breath that is not triggered by the patient) were present. Furthermore, most of the home ventilators were unable to cope with additional leaks, resulting in auto-triggering or in the inability to detect the patient's inspiratory effort [23]. Finally, significant differences with regard to the expiratory triggers were also observed in the French study, and some ventilators showed a low pressurization slope, which meant that the ventilator was not able to reach the preset pressure within a minimal time frame [23]. In conclusion, this study underlined the need for a systematic evaluation of all ventilators proposed for home ventilation in children. This evaluation should ideally include an assessment of the quality of the inspiratory and expiratory triggers and of the ability of the ventilator to reach and maintain the preset volume or pressure, as well as to cope with leaks [23].

In clinical practice, the use of a high backup rate, i.e., equivalent to two or three breaths below the patient's spontaneous respiratory frequency, may overcome the problems associated with an inadequate inspiratory trigger. In particular, such a setting is recommended for patients with NMDs [26].

7.7 Noninvasive and Invasive Long-Term Mechanical Ventilation

Interfaces are devices that connect ventilator tubing to the patient, facilitating the entry of pressurized gas into the upper airway. The major difference between invasive and NIV is that with the latter, gas is delivered to the airway through an "interface" rather than an invasive conduit.

NIV represents an interesting alternative to tracheotomy, which is associated with significant morbidity (i.e., tracheomalacia, granuloma formation, soft-tissue infections around the tracheostomy stoma, impaired swallowing) and may impair normal development and, particularly, language development [12,27,28]. Moreover, discomfort and disruption of social and family life are common consequences of patients with a tracheostomy. Finally, although tracheostomized children may be safely discharged home after careful family education and training, home treatment may be difficult or even impracticable for some families [29]. In contrast, home treatment is easier with NIV, which has the main advantage of being noninvasive with the possibility of an "on-demand" use, causing much less discomfort and social life disruption than a tracheotomy.

Several recent studies showed that the majority of children on LTMV are ventilated noninvasively [1,2,7]. While NIV has been used in children and adolescents suffering from severe obstructive sleep apnea syndrome (OSAS) and CRF due to NMDs or lung diseases, more recently it is also being used in younger patients and patients with various diseases associated to severe bilateral facial deformities, such as achondroplasia, craniostenosis, and Down syndrome [30–32]. Moreover, an increasing number of patients may benefit from NIV in the newborn period, such as infants with Pierre Robin syndrome [21,33].

Unfortunately NIV cannot be used with all children because of several reasons [19]: (1) NIV is more difficult to apply in infants and young children than in adults; (2) it requires a minimal respiratory autonomy; and (3) it may be ineffective in patients with severe bulbar involvement with recurrent pulmonary infection or in patients with severe retention of secretions not controlled by noninvasive measures. The inability to tolerate NIV for the amount of time required or ineffective NIV are other causes of NIV failure [12,15].

A recent Italian survey showed that the percentage of noninvasively ventilated patients increased with age, becoming prevalent in those older than 11 years [1]. Moreover, failure to wean from mechanical ventilation and the need for nearly continuous ventilatory assistance were the main causes leading to tracheotomy [1].

It is noteworthy that, in children with SMA type 1 and in other rapidly progressive NMDs, tracheotomy is controversial and an ethical dilemma [8]. Consequently, in these cases, tracheotomy for chronic ventilation is a decision that needs to be carefully discussed if requested by parents.

7.7.1 Noninvasive Long-Term Mechanical Ventilation

The choice of the optimal interface is of paramount importance for the success of NIV, but is also challenging, especially in young children and those with facial deformities. Consequently, the extended use of NIV is limited by the paucity of well-adapted industrial masks for these young children. Furthermore, children may not tolerate NIV in the case of skin injury, pain, discomfort, or air leaks around the mask. Finally, the choice of the interface for NIV is also determined by the ventilatory mode: interfaces with manufactured leaks are used for leak ventilation, while interfaces without manufactured leaks are used for non-leak ventilation.

In chronically, noninvasively ventilated children, five different types of interfaces may be used, i.e., nasal mask, oronasal mask, nasal prongs, mouthpieces, and full-face mask.

7.7.1.1 Nasal Mask

Nasal masks are preferred because they have less anatomical dead space, are less claustrophobic, and allow communication and expectoration more easily than full-face masks [19]. Nasal masks also allow the use of a pacifier in infants, which contributes to the better acceptance of NIV and the reduction of mouth leaks [19].

7.7.1.2 Oronasal Mask

Oronasal masks may be less acceptable to some patients for long-term use because they cover both the nose and mouth, and asphyxiation may be a concern in children who are unable to remove the mask in the event of ventilator malfunction or power failure (i.e., preschool children, children with NMDs, or reduced mobility of the upper limbs) [34]. Furthermore, interference with speech, eating, and expectoration, claustrophobic reactions, and the theoretical risk of aspiration

and rebreathing, are greater with oronasal than nasal masks. Consequently, in children, these interfaces are only used in the case of serious mouth leaks and/or the impossibility to close the mouth during sleep.

7.7.1.3 Nasal Prongs

Nasal prongs are very well tolerated by patients because of the absence of a frontal support, which allows the patient to continue to perform normal daily activities, such as reading, writing, and watching television without much hindrance. Furthermore, Ramirez and colleagues showed that exchanging a nasal mask with nasal prongs was associated with a marked reduction in maxillary retrusion in an adolescent who developed severe facial deformity within a few months after the start of NPPV [34]. However, nasal prongs are often too large for small children [19,34].

7.7.1.4 Mouthpieces

Mouthpieces, held in place by lip seals, are simple and inexpensive interfaces. They may be selectively used in older patients with NMDs [35]. Mouthpiece ventilation is especially useful for daytime ventilatory assistance. The mouthpiece can be placed near the mouth using clamp support, with ventilation supplied by a wheelchair-mounted portable ventilator. For nocturnal use, the mouthpiece is held in place by a strapless bite block. Although mouthpieces have been extensively used in patients with NMDs, they require good cooperation and are difficult to use in young children [19]. In addition, one of their major limitations is the production of large amounts of air leaks, which may compromise NIV efficacy and cause unwanted alarming of the ventilator. Moreover, mouthpieces may stimulate salivation, elicit the gag reflex and, ultimately, cause vomiting. Standard mouthpieces may also produce orthodontic deformities over time [36,37].

7.7.1.5 Full-Face Mask

A total full-face mask (i.e., PerforMax, Respironics, Murrysville, PA, USA) covers the nose, the mouth, and the eyes. By sealing around the perimeter of the face, where patients have less pressure sensitivity and smoother facial contours, it improves comfort, minimizes skin breakdown, and eliminates nasal bridge seal challenges. Although it is usually restricted to the acute setting, the author's experience (Racca and Gregoretti unpublished data) is that some pediatric patients (i.e., > 4 years) can selectively be adapted to this interface without an increase in CO_2 due to the greater dead space (unpublished data).

Custom-made masks may play a major role for infants and children who cannot use industrial masks [38]. Faroux and colleagues [38] found that skin injury was associated with the use of a commercial mask. In their study, the replacement of a commercial mask with a custom-made mask was associated with a reduction in the skin injury score.

A systematic close surveillance of the tolerance of the interface is mandatory in children treated with long-term NIV. First of all, the rapid growth of facial structures in young children is a frequent cause of mask change. Moreover, side effects

may be clinically significant in children using NIV, and the interface should be changed or modified at the first sign of intolerance (i.e., discomfort, inefficacy of NIV because of leaks, facial deformity). In these young patients, there is a high risk of skin injury. Faroux and colleagues found that skin injury due to a nasal mask, ranging from transient erythema to permanent skin necrosis, was observed in 53% of the 40 patients during their routine 6-month follow-up [38]. Other facial side effects are facial deformity, such as facial flattening and maxilla retrusion [39,40], caused by the pressure applied by the mask on growing facial structures. The long-term side effects of NIV in children, such as facial flattening or maxillary retrusion, should not be underestimated [38–40]. Thus, systematic close monitoring by a pediatric maxillofacial specialist is mandatory in children treated with long-term NIV [38].

Recently, Ramirez and colleagues reported their study of a large group of infants and children (i.e., 97 children) who were started on long-term NIV [34]. On admission, the most appropriate interface with regard to the patient's underlying disease and ventilatory mode, but also tolerance and comfort, was selected. The patients were tried on the interface with NIV for repeated short periods during the daytime. In infants and children nasal masks were preferred over facial masks, which were only used in the case of serious mouth leaks and/or the impossibility to close the mouth during sleep. In adolescents, nasal prongs were proposed as the first choice in the case of CPAP or BiPAP ventilation. The interface associated with the best tolerance and comfort, defined by the absence of any skin injury, pain, discomfort, and leaks, was selected. All 25 children aged ≤ 2 years, as well as four older children, were fitted with custom-made nasal masks; all other children were fitted with an industrial nasal mask (50%), a facial mask (16%), or nasal prongs (2%). Industrial masks with and without manufactured leaks were used in 33 (34%) and 35 (36%) children, respectively. All patients with obstructive sleep apnea used interfaces with manufactured leaks, whereas all patients with NMD or thoracic scoliosis used interfaces without manufactured leaks. Both types of interfaces were used in patients with lung disease. It is noteworthy that, in this study, even after a careful selection of the most appropriate interface by an experienced NIV and maxillofacial team, discomfort and side effects occurred in as many as 21% of the patients, justifying systematic and close monitoring of the NIV interface. The interface had to be changed in 20 patients because of discomfort (n = 16), leaks (n = 4), facial growth (n = 3), skin injury (n = 2), or change of the ventilatory mode (n = 2). A second or third mask change was necessary in nine and four patients, respectively [34].

7.7.2 Long-Term Mechanical Ventilation via Tracheostomy

Generally, small, plain tracheostomy tubes should be used [12]. These prevent tracheomalacia, and a large leak around the tracheostomy facilitates speech. Disposable plastic tracheostomy tubes under size 4 do not have an inner cannula and thus should be changed on a regular basis at home.

The majority of tracheostomized children are ventilated with VTV [1,12]. Ventilator-assisted children generally have uncuffed plain tracheostomies [1,12]. As a consequence, a portion of the TV delivered by the ventilator is leaked around the tracheostomy tube through the native airway. Because, in some children, this leak is relatively constant, a higher TV (e.g., 10–15 mL/kg) can be used to compensate the leak so that adequate ventilation can be achieved [12]. Otherwise, the tracheostomy leak can be compensated by using the ventilator in a pressure modality; alternatively, partially inflated cuffed tracheostomy tubes may be used [12].

Most children require tracheostomy tube changes in the range of weekly to monthly. However, frequency should depend on individual factors [12]. For example, changes may need to be more frequent during respiratory infections or in patients with increased tracheal secretions.

All caregivers, whether they are performing routine tracheostomy tube changes or not, should learn the technique in the event that an emergency or unexpected tracheostomy tube change is required. A second sterile tracheostomy tube must always be available in case of accidental decannulation. In addition, a tracheostomy tube with an external diameter smaller than the one in place should be available for an emergency maneuver (e.g., when the tracheostomy tube cannot be easily replaced) [12].

7.8 Additional Equipment for Pediatric Home Ventilation

7.8.1 Need for an Alternate Power Supply for the Ventilator

Supplemental batteries are indicated for home use when power failures are common, when patients may suffer adverse consequences during even brief power outages, and in cases where mobility is important [12]. In fact, a child who requires continuous ventilation should have a battery, not only to allow mobility in a wheelchair, but also to avoid catastrophic consequences in the event of a power failure. These batteries must be checked regularly to ensure proper function. Children requiring only nocturnal mechanical ventilation may not need a battery.

Backup generators may be useful in remote areas where power failures may be prolonged [12] .

7.8.2 Backup Ventilators

For children who have < 4 consecutive hours of free time from the ventilator, a backup ventilator is necessary because these children cannot tolerate the length of time that may be required for the provider to bring a functioning ventilator to the patient. Furthermore, backup ventilators are also necessary for children who live at a great distance from medical care or from their home providers [12].

Both ventilators should be used alternatively to assure that both remain functional.

7.8.3 Humidifiers

All patients receiving continuous mechanical ventilation through tracheostomy require that the inspired gas is warmed and humidified to prevent drying and thickening of tracheobronchial secretions. Humidifiers may be of the water reservoir type (bubble through or passover) or of the heat and moisture exchange type (artificial nose). Since water reservoir type humidifiers are more effective, they are recommended for all tracheostomized patients, except during short periods away from home [12]. During these short periods (< 12 h) away from the care setting, heat and moisture exchangers are preferred.

Humidifiers are not required in many patients using nasal or face mask ventilation, but are needed for patients in dry climates or during the winter months, or for patients using mouthpiece ventilation. A heat and moisture exchanger is not recommended because there is a large volume of gas moving through the device. In addition, these should be avoided with BiPAP devices because they add resistance and may alter the inspiratory and expiratory pressures [12].

7.8.4 Suction Machines and Suction Catheters

All patients receiving mechanical ventilation through tracheostomy require a portable suction machine. They should be electronically and battery-powered [12]. Although a sterile technique is mandatory in acute and intermediate care facilities as well as in long-term skilled nursing facilities, suctioning at home should be performed using a clean technique, with maintenance of standard precautions. In this technique, nondisposable suction catheters can be cleaned and reused [12].

7.8.5 Oxygen Therapy and Pulse Oximeter

The goal of home oxygen therapy is to maintain a sufficient PaO_2 to prevent the cardiovascular or central nervous system complications of hypoxia while optimizing the child's lifestyle and rehabilitative potential. This generally requires a PaO_2 > 65 mmHg (> 95% SpO_2 of hemoglobin) at sea level [12]. Oxygen should also be used for emergency rescue maneuvers.

If additional oxygen is required in ventilator-dependent children, liquid O_2 tanks should be used. Small portable cylinders allow for mobility of the oxygen-dependent child.

Because PaO_2 varies considerably with sleep, feeding, and physical activity, especially in infants and small children, continuous noninvasive monitoring techniques (i.e., pulse oximeter) should be used to assess the adequacy of oxygenation during periods of sleep, wakefulness, feeding, and physical activity.

Pulse oximeters should also be used in children with NMDs. Indeed, Bach and colleagues [41,42] described a regimen for managing acute-on-chronic neuro-

muscular respiratory failure at home, which includes the use of a pulse oximeter. The patient receives 24-h mechanical ventilation during exacerbation; pulse oximetry is monitored continuously and when SpO_2 on room air falls below 95%, secretions are aggressively removed with mechanical in-exsufflation (MI-E) until SpO_2 returns to 95%.

7.8.6 Monitoring

For most patients, a pulse oximeter is sufficient for adequate home monitoring. Capnography may be useful in selected patients [12].

7.8.7 Self-Inflating Resuscitation Bag

All patients receiving mechanical ventilation through tracheostomy require a self-inflating resuscitation bag with mask.

7.9 Noninvasive Aids for Secretion Clearance

NIV should be combined with airway clearance techniques for all patients with weakened expiratory muscles who have excessive secretions [8,9,12]. Airway clearance is very important in the chronic management of all patients with NMD. Indeed, effective airway clearance is critical for patients to prevent atelectasis and pneumonia. Ineffective airway clearance can hasten the onset of respiratory failure and death, whereas early intervention to improve airway clearance can prevent hospitalization and reduce the incidence of pneumonia [8,9,12].

Assessment of the patient's ability to clear secretions is done primarily by measuring peak cough flow (PCF). PCF can be obtained with a simple peak flow meter connected to a fitted mask while asking the child to cough. PCFs of 160–270 L/min have been described as acceptable levels to clear the airway in adults and adolescents. Below this point, patients are more susceptible to infection and respiratory failure [9,15]. Children with NMDs may be too weak or too young to perform this measurement. Therefore, the most useful evaluation of respiratory muscle function may be observation of cough ability [8].

Various techniques have been developed to overcome ineffective cough in patients with neuromuscular weakness. Noninvasive techniques for secretion clearance include manually assisted coughing and mechanical insufflator-exsufflator (MI-E). MI-E is usually employed when manually assisted coughing is inadequate. MI-E is contraindicated in patients with bullous emphysema or other disorders associated with a predisposition to barotraumas [12]. Oral suctioning can assist in managing secretions after assisted coughing [8]. Home pulse oximetry is useful to monitor

the effectiveness of airway clearance during respiratory illnesses. Caregivers should learn how to assist coughing in all patients with ineffective cough.

7.10 Home Discharge and Regular Follow-Up

Since discharging a ventilator-dependent child to home imposes a significant burden on the family, the physician should inform patient and family of such a burden, as well as the benefits of home LTMV.

Before the patient's home discharge, all caregivers must be trained and need to demonstrate competency in all the care procedures the patient will require. In particular, training should include the correct use of equipment and supplies. Moreover, parents of a LTMV child should be trained to recognize and correct the most common problems, such as tube dislocation or tube obstruction.

The planning of home LTMV requires communication between territorial and hospital structures. In particular, the general practitioner and local health service must be involved. Furthermore, nurses, physiotherapists, and speech therapists from territorial structures may be required at home.

Before children are discharged home, the equipment and supplies required for the continuation of ventilator assistance must be provided by the local health service. Furthermore, equipment companies should provide equipment maintenance and help in case of malfunction.

A written comprehensive management plan, covering both respiratory and other medical care, should be developed before discharge (Table 7.3). This plan should be based on the physician's instructions and used by the caregivers and ancillary personnel to guide them in the daily care of the child.

Finally, a scheduled regular follow-up program should be an essential element of the home discharge. Follow-up visits are justified and medically necessary for the evaluation of changes in clinical status and for care plan modifications when they are necessary. The patient in a stable condition should be seen by their physician, who should be experienced in the management of LTMV at appropriate intervals. More frequent visits are required immediately following home transfer and as warranted by the patient's medical condition. The ventilator-assisted patient can be transported to the physician's office.

7.11 Conclusions

Larger prospective studies are warranted to determine:

1. the criteria to initiate LTMV according to the patient's age and underlying disease;
2. the long-term benefits (i.e., increase in survival, stabilization in the decline in lung function and respiratory muscle performance);
3. whether LTMV may improve the child's and family's quality of life; and
4. the type of equipment and the specific ventilator settings that should be chosen.

Table 7.3 Care plan checklist

Mechanical ventilator, active humidifier, and ventilator circuit information:
- detailed description of circuits
- detailed description of ventilator power source
- instructions for cleaning and assembling the ventilator
- specific times on and off the ventilator
- description of mode of ventilation
- desired pressure and TV ranges
- description of alarms
- range of pulse oximetry
- equipment company phone number for help in case of ventilator malfunction

Name, size, and type of noninvasive interface (for noninvasive ventilatory support only)

Instructions for the care of the noninvasive interface (for noninvasive ventilatory support only)
- instructions for cleaning and assembling the interface
- instructions for reducing the risk of skin breakdown (e.g., barrier dressing, such as hydrocolloid sheet)
- instructions for securing the mask (e.g., avoid air leaks although allowing enough space to pass two fingers under the head strap)

Name, size, and type (cuffed or uncuffed, double or single cannula, fenestrated or not fenestrated) **of artificial airway** (for invasive ventilatory support only)

Instructions for the care of the artificial airway (for invasive ventilatory support only)
- conditions for inflation/deflation, if appropriate
- airway care plan (tube changes, cleaning, problem-solving)
- airway suctioning (detailed description of sterile technique for suctioning)
- medications

Description of self-inflating resuscitation bag use (for invasive ventilatory support only)

Adjunctive techniques
- pulse oximeter use
- oxygen therapy use, if appropriate
- secretion clearance devices use, if appropriate
- regimen for managing acute-on-chronic respiratory failure at home
- aerosol (bronchodilator), if appropriate
- chest physiotherapy, if appropriate

Notification of local emergency care facilities

Equipment and supplies for LTMV (e.g., interfaces or tracheostomy tube, ventilator circuits, and so on) **prescribed and provided at home**

First follow-up program scheduled

Documentation of the education of caregivers

Other medical care

LTMV long-term mechanical ventilation, *TV* tidal volume

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