

## CHAPTER 4

# Respiratory muscle assessment

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Respiratory muscles generate the pressure differences driving ventilation. Respiratory muscle weakness is hence an important clinical feature. In advanced stages, respiratory muscle weakness leads to respiratory pump failure. Respiratory muscle dysfunction (*i.e.* reduced strength or endurance) is to be distinguished from lung function abnormalities, and should be measured separately. Inspiratory muscle weakness may partially explain dyspnoea and exercise intolerance. In addition, reduced respiratory muscle force has been shown to be an important predictive factor for poor survival in chronic obstructive pulmonary disease (COPD) [1], cystic fibrosis [2] and congestive heart failure [3]. In advanced stages the functional consequence of respiratory muscle weakness is a reduction of the operational lung volume and patients may require mechanical ventilation. Expiratory muscle weakness leads to problems with speech, and mucus retention due to impaired cough efficacy.

Measurement of respiratory muscle function is important in the diagnosis of respiratory muscle disease [4–6], or respiratory muscle dysfunction [7]. It may also be helpful in the assessment of the impact of chronic diseases [8–12] or their treatment [13–15] on the respiratory muscles. For example, specific inspiratory muscle training has been reported to be useful in COPD only when patients present with significant respiratory muscle weakness [15], and tapering of oral corticosteroid treatment successfully restored respiratory muscle strength and dyspnoea in patients with corticosteroid-induced myopathy [16].

The present chapter aims to provide clinicians with some aspects of respiratory muscle testing. More detailed, excellent reviews on the pathophysiology and aetiology of respiratory muscle weakness are available elsewhere for the interested reader [17, 18]. Indications, techniques commonly used in clinical practice and issues important in the interpretation of the test results are the main focus of this chapter.

## When should respiratory muscle function be assessed?

Measurements of respiratory muscle function should be performed as part of a more complete diagnostic process including anamnesis and physical examination, arterial blood gas analysis and imaging techniques. Lung function assessment including spirometry, assessment of static lung volumes, and diffusion capacity further completes the technical investigations relevant in the diagnostic process. Measurements of

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respiratory muscle strength or endurance should never be over-interpreted. A low inspiratory or expiratory muscle strength without clinical context has relatively poorly defined clinical consequences and the range of normality in healthy subjects is very large [19]. The clinician may encounter two possibilities that would prompt for careful assessment of respiratory muscle function: 1) clinical signs or symptoms that are suggestive of respiratory muscle weakness; or 2) a pathological condition where respiratory muscle weakness may occur and assessment of the respiratory muscles is advised in the screening, prevention, or follow-up of these patients.

### ***Clinical signs of respiratory muscle weakness***

Clinical signs or symptoms that can be suggestive of respiratory muscle weakness can be summarised as follows: 1) unexplained reduction in vital capacity; 2) CO<sub>2</sub> retention while awake or during sleep, specifically in the absence of severe airflow obstruction; 3) shortness of breath; 4) orthopnoea (shortness of breath while supine), or dyspnoea during bathing or swimming; 5) short sentences during speech; 6) tachypnoea; 7) paradoxical movement of the abdominal or thoracic wall; 8) problems with cough (and recurrent infections); and 9) generalised muscle weakness.

Respiratory muscle weakness is often advanced before clinical symptoms occur. This follows from the relatively low respiratory muscle force that is required to overcome most respiratory tasks. In addition, symptoms only poorly relate to measurements of respiratory muscle strength or endurance. In patients with neuromuscular disease, for instance, hypercapnia only modestly relates to respiratory muscle strength [5, 20]. This is due to the fact that symptoms generally only occur in the presence of an imbalance between the load on the respiratory pump and its capacity [21]. Respiratory muscle function measurements address only the latter.

When respiratory muscle strength is moderately to severely reduced, discrete clinical symptoms may occur, and this may prompt for assessment of the respiratory muscles to help in the diagnostic process. The cardinal symptom of respiratory muscle weakness is dyspnoea. When muscle weakness becomes more obvious, symptoms may also occur at rest, dyspnoea, hypercapnia and/or speech problems disable the patient. In the case of severe expiratory muscle weakness, reduced cough efficiency may become an important handicap and patients may become ventilator dependent. Only in severe respiratory muscle dysfunction, vital capacity is generally reduced as a consequence of the respiratory muscle weakness and may become a better predictor of morbidity than measurements of respiratory muscle strength [22].

### ***Pathological conditions in which respiratory muscle weakness can be suspected***

Patients with neuromuscular or metabolic diseases are obviously at risk to develop skeletal and respiratory muscle weakness. In some cases the respiratory muscle weakness and related symptoms are even the first presenting symptoms [23, 24]. In neuromuscular diseases close attention should be paid to the involvement of both the inspiratory and the expiratory muscles. In patients with multiple sclerosis for example, abdominal (and hence expiratory) muscle weakness is a hallmark of the disease [25], and is related to clinical problems, such as mucus retention. In lung diseases, such as cystic fibrosis and COPD, inspiratory muscle weakness is often present [26]. As a contradiction at first sight, respiratory muscles seem, on average, to be relatively well trained in these diseases [27–29]. The low respiratory pressures are due to the mechanical constraints and hyperinflation rather than to pure muscle weakness. When patients are malnourished or exposed to corticosteroids, however, weakness of the respiratory muscles is seen in these diseases [13, 30, 31]. Some attention has recently been given to expiratory muscle

weakness in obstructive lung diseases. Abdominal muscle strength was more than normal in cystic fibrosis [27], probably as a consequence of the chronic coughing. In COPD patients, expiratory muscle weakness is seen frequently [32, 33], but the clinical importance of it is not well understood.

Less obvious, but nonetheless important is the detection of respiratory muscle weakness in patients with heart failure [9], cancer [34] and systemic diseases, such as sarcoidosis [12, 35, 36]. In patients diagnosed with hyperventilation [37] and asthma [38, 39], respiratory muscle weakness can contribute to the sensation of dyspnoea and the assessment of respiratory muscle function may be helpful in solving the diagnostic dilemma of unexplained dyspnoea.

When patients are treated with drugs that may induce myopathy, it may be prudent to assess respiratory muscle strength before initiating the treatment, and proper follow-up of patients is advised [40]. After corticosteroid treatment, respiratory muscle function is often impaired [16], and long-term colchicine treatment may also induce respiratory muscle weakness [41]. Hence the assessment of respiratory muscle function is surely not restricted to patients with pulmonary diseases.

## Principles of assessment of respiratory muscles

Measurement of respiratory muscle strength is no novelty in the lung function laboratory [42]. It is nowadays routinely performed in clinical practice as tools have become available that allow these measurements to be performed routinely in clinical practice. The interpretation of measurements of respiratory muscle strength, however, may be somewhat more complex than most other measurements of skeletal muscle strength, for the reasons described below.

In clinical practice respiratory muscle force is indirectly measured through the pressure generated during inspiration or expiration. Respiratory muscle force is generally expressed as kilopascal (kPa) or cm water pressure (cmH<sub>2</sub>O: 1 kPa=10.2 cmH<sub>2</sub>O). These pressures reflect pressure changes against atmospheric pressure. The pressure is generated by all the muscles under investigation (inspiratory or expiratory), and is hence not muscle specific. In addition, reduced respiratory muscle force may result from cerebral, spinal cord, anterior horn, peripheral (*i.e.* phrenic) nerve, neuromuscular junction or the muscle fibre dysfunction. At each level pathology may occur and hence reduced respiratory pressures should not be necessarily attributed to a respiratory muscle dysfunction *per se*. The pressures measured depend also on the geometry of the thorax in which the pressure is generated. For instance, the pressure generated by the diaphragm is dependent of its *in vivo* three dimensional shape taking into account: 1) Laplace law (in brief, the Laplace law implies an inverse relationship between the radius and the pressure); 2) the relative degree to which it is apposed to the rib cage; and 3) its length force properties [43]. In stable patients with emphysema, the "flattened" diaphragm often fails to generate normal pressure, although the diaphragm muscle is generally believed to be well "trained" [28, 44–46].

Another variable influencing the outcome of the inspiratory and expiratory pressure measurement is the relative lung volume at which it is obtained. Like all skeletal muscles, the respiratory muscles have a well defined length–tension relationship. If the diaphragm is shortened below its optimal length ( $L_0$ , the length at which a maximal tension is obtained) it can generate less tension [47]. This has repercussions during acute hyperinflation, where the mechanism of reduced tension generating capacity of the diaphragm seems to be more important than the geometric changes [48]. The length–tension relationship has important consequences for the technique of measuring

in- and expiratory muscle force. Indeed, changes in the lung volume at which the measurement is performed may alter the outcome of the measurement. Hence, lung volumes should be properly standardised.

A final factor, related to the above, influencing the pressure measured during maximal inspiratory or expiratory manoeuvres, is the elastic recoil of the lungs (inward) and chest wall (outward). At the functional residual capacity the elastic recoil of the lungs and the chest wall generate equal pressures. Hence, at this lung volume any additional pressure measured during in- or expiration originates exclusively from respiratory muscle activation. When expiratory pressures are measured at total lung capacity (TLC), the recorded pressures are the result of the expiratory muscle and the elastic lung recoil at TLC. Alternatively, when inspiratory pressures are assessed at residual volume (RV), the resultant pressures originate from the action of the inspiratory muscles, and the pressure generated by the tendency of the chest wall to expand at RV.

Taking the above into account, clinicians should be aware that the respiratory pressures obtained in patients, or healthy subjects are not a "clean" measure of the strength of the respiratory muscles. They are the net result of the tension (force) generated by the muscle, which is dependent on the lung volume at which the manoeuvre is obtained and the chest wall and lung mechanics. Elastic recoil is also dependent on the lung volume, but may also be altered by the disease (*e.g.* lung fibrosis *versus* emphysema). The resulting pressures are, however, a good reflection of the functional reserve of the respiratory pump, since the net pressure generated is needed to drive the ventilation.

## Measuring respiratory muscle force

Measurements of respiratory muscle function are generally obtained from measuring pressures achieved by volitional activation or electrical or magnetical stimulation of the phrenic nerve or motor roots. Pressure can be measured in the nose, at the mouth, in the oesophagus, or across the diaphragm (measuring the pressure above, in the oesophagus, and below the diaphragm, in the stomach). Lung function impairment (static and dynamic lung volumes) does not correlate with respiratory muscle dysfunction, with the exception of patients with neuromuscular disease in advanced stages. Techniques used in the lung function laboratory are described below.

### *Maximal voluntary respiratory pressures measured at the mouth*

Maximal voluntary inspiratory ( $PI_{max}$ ) and expiratory ( $PE_{max}$ ) pressures (or MIP and MEP) are probably the most frequently reported noninvasive estimates of respiratory muscle force. Ever since BLACK and HYATT [42] reported this noninvasive technique in the late 1960s it has been widely used in patients, healthy control subjects across all ages, and athletes. Pressure is recorded at the mouth during a quasi-static short (few seconds) maximal inspiration (Müller manoeuvre) or expiration (Valsalva manoeuvre). No airflow is allowed during the manoeuvre and pressure can build up to >30 kPa in extremely fit healthy subjects. The manoeuvre is generally performed at RV for  $PI_{max}$ , and at TLC for  $PE_{max}$ . Although functional residual capacity would theoretically be more appropriate, as lung and chest wall compliance are neutralised, and the pressure theoretically would better reflect the tension developed by the respiratory muscles ( $P_{mus}$ ), patients find it easier and more straightforward to perform the manoeuvres from RV and TLC. Only few contraindications exist for these measurements and these can be summarised as pathological conditions where relatively large pressure swings in the thorax or abdomen

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should be avoided (e.g. aneurism, uncontrolled hypertension, urinary incontinence). The coefficient of variation is reported to be acceptable for a clinical test (6–9%) [49–51].

Although the technique appears simple at first sight and hard- and software became available to make these measurements easily accessible in the pulmonary function laboratory, there are some technical pitfalls that may influence the obtained results and make the results more variable than most other lung function measurements. Some critical aspects in the methodology are summarised below.

**Tracing inspection.** Quality control of the measurements can only be obtained from inspection of the pressure–time curves. The peak pressure should be obtained in the very beginning of the manoeuvre. The pressure maintained for at least 1 s is generally reported as the  $P_{I,max}$  or  $P_{E,max}$  (plateau pressure) [17]. A recent study, however, challenged the use of the plateau pressure, concluding that the peak pressure may be easier to obtain and equally reliable when subjects are well instructed [52].

**Position.** Measurements are obtained preferably in the sitting position. Although body posture has no significant influence on the result of the measurement in healthy subjects [53], and even in convalescent neonates [54], in COPD patients changes in body posture may significantly impact on the obtained result. Leaning forward for example may result in higher inspiratory pressures [55], while measurements obtained in the recumbent position may lead to lower pressures [56].

**Leak.** To avoid pressure generation by the muscles of the cheeks and buccal muscles, a small leak should be present in the equipment. The leak described by Black is 15 mm long and has an internal diameter of 2 mm. Using this leak, the glottis should be opened to generate pressures for >1 s, and the pressure obtained reflects the pressure generated by the respiratory muscles. When a leak is absent, the recorded pressures may erroneously reflect the pressure generated in the mouth by the cheeks and buccal muscles.

**Mouthpiece.** Flanged mouthpieces (as the ones generally used for lung function testing) have been reported to result in pressures inferior to those obtained when a rigid mouthpiece is sealed against the mouth. Especially for expiratory pressures, flanged mouthpieces may result in underestimated pressures due to additional leaks that appear with the increased pressure in the mouth [57]. Sometimes tests can be more successfully performed using a face mask (especially in patients with neuromuscular diseases characterised by facial or bulbar muscle weakness). On average there is no significant difference in  $P_{I,max}$ , but  $P_{E,max}$  may be higher using a tube or nonflanged mouthpiece [58].

**Practice tests.** Tests should be performed by an experienced technician. Since the Valsalva or Müller manoeuvres are unfamiliar to patients the manoeuvres should be carefully explained. There has been debate on the number of repetitions that need to be carried out before a result can be considered valid [59–62]. The current authors' experience, shared by others [19], suggests that a minimum of five manoeuvres should be performed, and reproducibility should be within 5–10%. Increasing the number of measurements is time consuming and tedious. In case of questionable effort, a sniff nasal pressure manoeuvre (see below) may give additional information.

**Equipment.** A recent statement of the American Thoracic Society and European Respiratory Society advises to use metal membrane or piezoelectric transducers with an accuracy of 0.049 kPa (0.5cmH<sub>2</sub>O) in a pressure range of  $\pm 19.6$  kPa ( $\pm 200$  cmH<sub>2</sub>O). When healthy subjects are tested, higher expiratory pressures may be obtained. In a cohort of 85

healthy subjects, tested in the current authors' laboratory and aged >50 yrs, the maximum inspiratory and expiratory pressure obtained were -17.6 kPa (-180 cmH<sub>2</sub>O) and 30.2 kPa (308 cmH<sub>2</sub>O) respectively.

It is preferred that the signal of pressure *versus* time is recorded, and is available to the technician for immediate inspection. Calibration of the manometer should be carried out regularly, and can be done easily using a water column. Mercury is preferably not used due to contamination problems.

**Interpretation and normal values.** In absolute numbers, the  $PE_{\max}$  is roughly the double of  $PI_{\max}$  when the Black and Hyatt technique is used, with a rigid mouthpiece. In this case it is very rare to find  $PE_{\max}$  inferior to  $PI_{\max}$ . This is illustrated in figure 1. However, in some diseases (*e.g.* spinal cord injury, below C3-5, multiple sclerosis)  $PE_{\max}$  is typically more reduced than  $PI_{\max}$ , and the value of  $PE_{\max}$  may be inferior to  $PI_{\max}$  (fig. 1). In addition, when a flanged mouthpiece is used, the  $PE_{\max}$  may often be underestimated due to leaks.

Many authors have reported normal values for  $PI_{\max}$  and  $PE_{\max}$ . Impressive differences are observed between the normal values [19, 58, 62–71] reported in the literature. This variability is depicted in figure 2 where an overview of available sets of normal male subjects is given as a function of age. Roughly, it can be seen that there is a decline of inspiratory muscle force from the age of 20–25 yrs. Hence if children are tested, separate normal values are advised. This is largely due to the previously described differences in methodology (lung volume, mouthpiece, number of repetitions). It is advised that a cohort of healthy subjects is tested and consequently the most appropriate

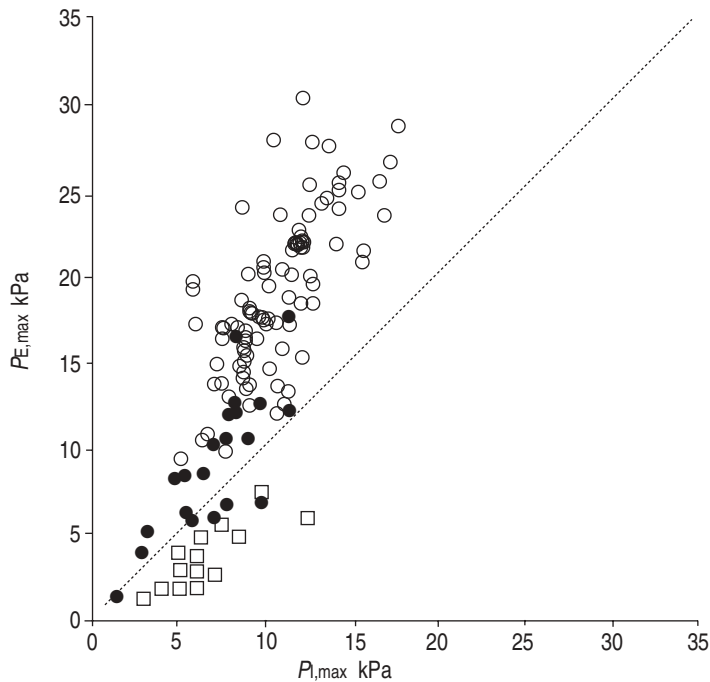


Fig. 1. – Maximum inspiratory and expiratory pressure ( $PI_{\max}$  and  $PE_{\max}$ ) measured in 85 healthy subjects (○), 21 patients with multiple sclerosis (MS; ●) tested in the current authors' centre [99], and 13 patients with spinal cord injury (SCI; □) [100]. As can be observed, in healthy subjects the  $PE_{\max}$  exceeds the  $PI_{\max}$  in every single case. In MS,  $PI_{\max}$  may be larger than  $PE_{\max}$ , and in SCI,  $PI_{\max}$  is typically larger than  $PE_{\max}$ .

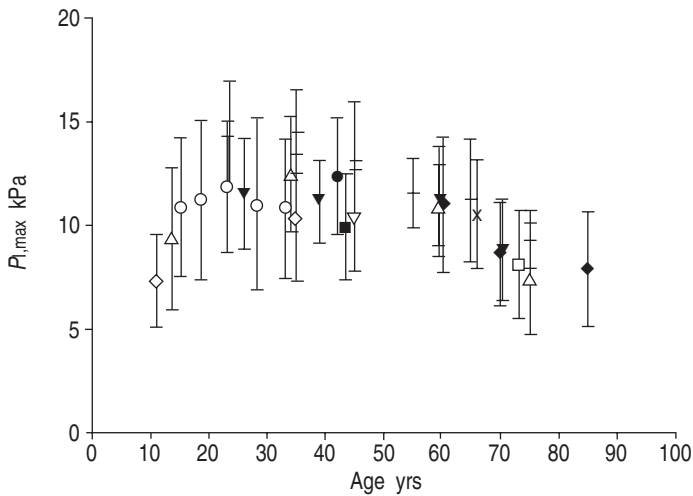


Fig. 2. – Predicted normal inspiratory pressures measured at the mouth for healthy male subjects as reported from the different cohorts reported in the literature. Maximum inspiratory pressure ( $P_{I,max}$ ) is reported in  $\text{cmH}_2\text{O}$ , age in years. Symbols represent different studies:  $\blacklozenge$ : WIJKSTRA *et al.*, 1995 [62];  $\blacktriangledown$ : ULDRY and FITTING, 1995 [72];  $\triangle$ : ROCHESTER and ARORA, 1983 [64];  $\blacksquare$ : HAUTMANN *et al.*, 2000 [70];  $\bullet$ : HEIJDRRA *et al.*, 1994 [56];  $\square$ : ENRIGHT *et al.*, 1994 [19];  $\nabla$ : VINCKEN *et al.*, 1987 [65];  $\circ$ : LEECH *et al.*, 1983 [68];  $\diamond$ : WILSON *et al.*, 1984 [67];  $\times$ : MCELVANEY *et al.*, 1989 [69];  $+$ : RINGQVIST, 1966 [66].

reference values are chosen. In addition, it has to be noted that in all models of maximal in- and expiratory pressures the explained variance is low, reflecting large inter-individual differences even when age, sex and anthropometric values are taken into account. Hence, a low  $P_{I,max}$  should always be interpreted with caution. A normal  $P_{I,max}$ , however, generally excludes clinically relevant inspiratory muscle pathology.

### *Inspiratory pressure measured at the nose*

$P_{I,max}$  measured at the nostril  $P_{sniff}$  during a sniff manoeuvre is a relatively newly developed technique [73] to measure inspiratory muscle function. One of the main advantages is that it is a technique that involves a natural manoeuvre (sniff), which is "easy to understand" by the patient [74]. Pressure is measured in an occluded nostril during a forced sniff. The unoccluded nostril serves as a variable resistance, prohibiting flow  $>30 \text{ L}\cdot\text{min}^{-1}$ , and the pressures measured at the nose reflect those obtained in the oesophagus during sniff manoeuvre [73]. Since there is more airflow compared with the  $P_{I,max}$  manoeuvre, these sniff manoeuvres are not static. Generally the sniff nasal pressures are as high as  $P_{I,max}$  (or even slightly higher) [72]. MAILLARD *et al.* [49] reported a  $P_{sniff}/P_{I,max}$  ratio of  $1.03\pm 0.17$ , and reported equal and good within session reproducibility. Although less common in routine clinical practice this technique showed to be extremely useful in the diagnosis and follow-up of respiratory muscle weakness in children [75, 76], and patients with neuromuscular disease [77, 78] where sniff nasal pressures were reported to be superior to  $P_{I,max}$ . It should be acknowledged that some investigators reported sniff nasal pressures to be inferior to  $P_{I,max}$  in severe neuromuscular disease [79]. Hence, in patients with low  $P_{I,max}$ , the addition of sniff nasal pressures further improved the diagnostic process and some patients were consequently classified with normal respiratory muscle force [80]. The two techniques should hence be considered complementary, rather than interchangeable. Normal values for the sniff

nasal pressure are available [72]. Sniff measurements may be problematic in patients with significant upper airway disease. Since the sniff is a very short manoeuvre, damping of the pressure from the oesophagus to the mouth and nose may occur in patients with obstructive lung disease, such as cystic fibrosis [76].

Much like the  $P_{I,max}$ , the sniff nasal pressure reflects a global measure of inspiratory muscle strength and not of diaphragm strength [74].

**Equipment.** Essentially the equipment can consist of the same pressure transducer as the one used in the assessment of the  $P_{I,max}$ . A perforated plug with a tube is used to occlude the nostril. The tube is connected to the pressure transducer and the pressure–time curve is recorded for inspection and quality control. The peak pressure is reported after a series of maximal sniffs separated by normal breathing. A plateau is generally obtained after 5–10 sniffs. As the sniff pressure is a very brisk manoeuvre the recording of the trace should be done with high resolution to allow detection of the peak pressure. Currently these devices, and accompanying software, are commercially available.

### ***Measurement in oesophagus or stomach***

In rare clinical cases, and to answer specific research questions, it may be useful to measure the pressure in the oesophagus or in the gastric area. In the oesophagus the pressure ( $P_{oes}$ ) is a reflection of the pleural pressure ( $P_{pl}$ ); the gastric pressure reflects the abdominal pressure ( $P_{abd}$ ). The difference between both pressures is the "transdiaphragmatic pressure" ( $P_{di}$ ), which is a more specific measure of diaphragmatic function.

To obtain these pressures a latex balloon catheter is put in place. Generally this is done by swallowing a balloon catheter introduced in the nose, after application of a local anaesthetic spray to the nasal mucosa and the pharynx. Double lumen catheters are available for simultaneous measurements of pressure above and below the diaphragm ( $P_{di}$ ). Balloons placed over the catheters are 5–10 cm long, have thin walls and are filled with ~0.5mL of air to allow proper transmission of the pressure into the catheter. Catheter mounted microtransducers are an alternative to the "classical" balloon catheters. These transducers are accurate, but measure pressure only at one spot. Hence the measurement obtained may be a less precise reflection of the overall  $P_{oes}$ . In addition, these catheters are much more expensive [17].

These tests are perceived by many patients as rather uncomfortable, but the results give probably the best estimate of the pressures generated by the respiratory muscles during normal breathing, during exercise, or during static manoeuvres or sniffs. When the balloon is positioned in the stomach, gastric pressure can also be recorded during cough. Hence "cough" pressure is recorded ( $P_{cough}$ ) [81]. In healthy subjects,  $P_{cough}$  was reported to be superior to  $P_{E,max}$ , and the lower limit of normal is set at 12.9 kPa (132 cmH<sub>2</sub>O) for male and 9.5 kPa (97 cmH<sub>2</sub>O) for female subjects. Recently,  $P_{cough}$  were found to be a useful addition in the diagnosis of expiratory muscle weakness. In a significant number of patients with low  $P_{E,max}$ ,  $P_{cough}$  was reported normal. By contrast only a few patients with normal  $P_{E,max}$  exhibited low  $P_{cough}$  [81]. As a noninvasive variant of  $P_{cough}$  CHETTA *et al.* [82] recently introduced the "whistle" pressures, measured at the mouth. Subjects were asked to perform a short, sharp blow as hard as possible from TLC through a reversed paediatric inhaler whistle.

### ***Nonvolitional tests of respiratory muscle function***

Measurements of maximal voluntary inspiratory or expiratory pressures at the mouth, nose, or even using balloon catheters to measure oesophagus or gastric pressures, are



biased by the motivation of the patient to collaborate with the tests. Maximal effort is sometimes difficult to ascertain because of lack of patient motivation, anxiety, pain or discomfort, submaximal central activation, poor mental status or difficulties in understanding the manoeuvres.

To overcome the issue of submaximal (voluntary) activation, investigation of the diaphragmatic function can be done through electrical [83] or magnetic [84] stimulation of the phrenic nerve. The diaphragm is exclusively innervated by the phrenic nerve (left and right). This nerve passes superficially in the neck and can be stimulated relatively easily. In addition, electromyography of the costal diaphragm can be carried out. When the latter is done, the phrenic nerve latency can be studied [85, 86], which allows lesions of the phrenic nerve to be detected. Pressures developed after twitch stimulation of the phrenic nerve can be measured transdiaphragmatically, or at the mouth. Although this technique is not often used in clinical routine, there are specific situations in which it may provide useful and unique information [87].

## Respiratory muscle endurance

Although maximal in- and expiratory muscle strength gives important information on respiratory muscle function, the respiratory muscles (especially the inspiratory muscles) should be able to cope with endurance tasks. Measurements of respiratory muscle endurance, therefore, give clinicians further insight in the function of the respiratory pump, and may unmask early task failure. In the authors' opinion, measurements of inspiratory muscle endurance are especially helpful when inspiratory muscle weakness is discrete, and its clinical consequence is unclear. In the clinic, respiratory muscle endurance is generally assessed using one of the following techniques:

### *Maximal sustainable voluntary ventilation*

The maximal sustainable voluntary ventilation (MSVV) is measured, or estimated from protocols with incremental ventilation [88]. The achieved sustainable ventilation is then reported as a fraction of the actually measured 12–15 s maximum voluntary ventilation (MVV), and/or as a fraction of the predicted MVV. MSVV should be ~60–80% of the 12 second MVV. This test can be considered as a test of in- and expiratory muscles, but it is relatively sensitive to changes in airway obstruction, and needs careful control and adjustment of CO<sub>2</sub> tension in arterial blood, by adding or removing dead space or CO<sub>2</sub> to the inspired air. In patients with severe airflow obstruction, MVV may be low due to important dynamic compression of the airways during the vigorous 12 s manoeuvre. Therefore, MSVV/MVV may seem relatively high in these patients, whereas other measurements of endurance showed reduced respiratory muscle endurance in COPD [89]. In a variant of this test proposed for COPD patients, patients are asked to sustain a ventilation of 66–75% of their MVV [90]. This test allows comparison within one subject, but normal values are not available.

### *Incremental threshold loading*

Patients are asked to breath against increasing inspiratory loads. The inspiratory threshold load is increased every 2 min [91]. The test can be compared with an incremental exercise test. The highest pressure that patients can sustain for 2 min in the incremental protocol is called maximum threshold pressure ( $P_{thmax}$ ). Generally patients should be able to reach a pressure equivalent to 75–80% of  $P_{I,max}$ . JOHNSON *et al.* [92]

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reported that the  $P_{thmax}/P_{I,max}$  was dependent on age. Important learning curves are reported for this test, and the test should be repeated at least two to three times [93, 94]. One study, conducted in COPD patients confirms the learning curve for the  $P_{thmax}$  at which patients could continue breathing, but since  $P_{I,max}$  showed a similar learning curves, the  $P_{thmax}/P_{I,max}$  ratio remained constant (61% in test 1 and 67% in test 4) [95]. Due to the incremental nature of the test, however, it can be criticised as a straightforward measure of endurance. Alternatively, the maximum sustainable threshold load can be determined. The sustainable load is the load that can be sustained for >10 min. This technique reflects better the concept of "endurance", but it is time consuming.

Recently, an expiratory incremental threshold loading test was developed, and used in healthy subjects and subjects with COPD [32]. Interestingly, the authors reported that the expiratory pressure that was achieved following an incremental protocol was only 44% of  $P_{E,max}$  in COPD. In healthy subjects 87% of  $P_{E,max}$  was reached. The clinical consequences of these findings may be illustrated by the recent finding that expiratory muscle training in COPD may be a successful training strategy to improve exercise capacity and dyspnoea in patients with COPD [33]. Further studies, however, should be conducted to assess the usefulness of such an intervention on a larger scale.

### ***Endurance time at a given threshold intensity***

From the work of NICKERSON and KEENS [96], and others [91, 97] it can be deduced that an inspiratory load of 60% of the  $P_{I,max}$  can generally be sustained for >10 min. As a simple test of respiratory muscle endurance, hence, patients can be asked to breath at a fixed inspiratory load equal to 60% of  $P_{I,max}$ . When subjects fail to continue breathing against this resistance at any time point earlier than 10 min, respiratory muscle endurance can be assumed impaired. Although easy to apply in clinical routine, this test has many methodological problems that impair the use of this test in clinical studies. The most important problem is probably the fact that the time to fatigue is related to the breathing pattern (*i.e.* the inspiratory time ( $T_I$ )/total respiratory time ( $T_{tot}$ ) ratio). The higher this ratio, the sooner fatigue will occur. Hence  $T_I/T_{tot}$  should be carefully controlled and maintained at  $\sim 0.4$  during the test [98]. Despite these methodological shortcomings the present authors use this test as a useful addition to a measurement of  $P_{I,max}$  in patients presenting with muscle weakness. In this case the test may give clinicians information on the susceptibility to inspiratory muscle fatigue. In patients with normal inspiratory muscle strength, the test is considered of less clinical value, as the pressures that should be sustained are far from those achieved in physiological conditions.

## **Conclusions**

The measurement of respiratory muscle force evolved from a technique used in clinical physiology studies to a measurement that gained importance in the clinical routine. Assessment of respiratory muscle force is extremely useful to understand the aetiology of dyspnoea, and the detection of respiratory muscle weakness has consequences in the treatment of patients. The most obvious example is the introduction of respiratory muscle training in patients with respiratory muscle weakness. Measurement of respiratory muscle strength is not restricted to patients with lung disease and should also be carried out in neuromuscular, systemic and cardiologic disease. In addition, in the follow-up of patients treated with drugs that may induce myopathy, the assessment of respiratory muscle function is advised. In the large majority of cases the assessment of

maximal inspiratory pressures give sufficient information to clinicians. In rare cases measurements of pressures in the abdomen or oesophagus may be needed. In a limited number of laboratories nonvolitional assessment of the respiratory muscles is done through magnetical or electrical stimulation of the phrenic nerve.

## Summary

Respiratory muscle weakness has serious clinical consequences. The assessment of respiratory muscle function and the detection of respiratory muscle weakness has a place in the clinical decision tree of many diseases, including lung disease, neuromuscular diseases and others. Equipment to measure respiratory muscle strength has become available and assessment of respiratory muscle force through the assessment of maximal in- and expiratory pressures at the mouth ( $P_{I,max}$ ,  $P_{E,max}$ ), has become a routine assessment in many lung function laboratories. In rare cases more elaborate measurements, including transdiaphragmatic pressures, cough pressures or measurements applying electrical or magnetical stimulation of the phrenic nerve, can be helpful in the diagnostic process. Clinicians should be aware that respiratory muscle force is approached indirectly by measuring the pressure generated by the respiratory pump. The mechanics of the pump should be taken into account when interpreting the results. Normal values are available, but large variability is present. Part of this variability is explained by the methodological differences described in this chapter.

Nevertheless, since respiratory muscle weakness can be treated in many cases by respiratory muscle training, or tapering of treatment with drugs that may induce respiratory muscle weakness (*e.g.* corticosteroids) or may help clinicians decide on mechanical ventilation strategies, knowledge of respiratory muscle dysfunction opens a window of clinical treatment opportunities. Hence, properly performed assessment of respiratory muscle function should be possible in any well-equipped lung function laboratory.

**Keywords:** Dyspnoea, muscle force, respiratory muscle.

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