

CLINICAL COMPENDIUM OF RESPIRATORY MUSCLE TESTING

Hans-Joachim Kabitz
 Respiratory Physiology Research Group
 University Hospital of Freiburg
 Department of Pneumology

Introduction

The main goal of the ventilatory system is to ensure delivery of oxygen to tissues and evacuation of carbon dioxide^{1,2}. Insufficient ventilation leads to alveolar hypoventilation with subsequent hypoxemia and hypercapnia (ventilatory/type II failure). The respiratory pump represents the principal component of the ventilatory system (Figure 1).

Fig 1. The Respiratory Pump

Complex neuronal pathways regulate ventilation via the respiratory centre located in the medulla oblongata. Synaptic transmission from the 1st to the 2nd motor neuron is followed by the motor endplate and finally by the contraction of respiratory muscle fibers. As for all skeletal muscles the same physiological principals apply for respiratory muscles^{2,3}.

Ventilatory failure is always linked to inspiratory muscle failure. This failure results from an imbalance between the capacity and the load imposed on the respiratory pump^{1,2,4}. Impaired ventilation can result from both an increase in load (e.g. interstitial lung disease), a reduction in capacity (e.g. myopathic disorders) or from the combination of both (e.g. COPD).

Two major questions are addressed by respiratory muscle testing:^{2,4}

1. Are the respiratory muscles impaired, and if so, how severely?
2. Is the demand on the respiratory muscles increased and how severe is it?

By answering these questions the differential diagnoses, particularly in the case of latent or manifest ventilatory insufficiency, are narrowed down. In addition, quantifying respiratory muscle function serves as an important progression parameter in different diseases and is used for therapy monitoring (e.g. COPD, neuromuscular diseases, non-invasive ventilation).

The objective of this review is to provide the reader with the needed information of how to apply each particular method of respiratory muscle testing in addition to the discussion of the most important basic characteristics of each method.

Methods

Clinical signs and symptoms (e.g. dyspnea under

exertion, tachypnea, paradox ventilation) lead the way to suspect ventilatory failure. Lung function testing and blood gas analysis are essential and need to be supplemented by different tests assessing respiratory muscle strength and related ventilatory characteristics^{4,5}. Two major categories of respiratory muscle tests exist: volitional and non-volitional tests. It is the combination of the tests that establishes a reliable diagnosis. Selective respiratory muscle weakness (e.g. isolated diaphragmatic dysfunction in the presence of phrenic nerve palsy) can escape detection by certain tests. It is therefore highly recommended to perform complete respiratory muscle testing and to include all of the available tests in all cases of suspected respiratory muscle dysfunction. Screening is performed by volitional and non-invasive tests. In the event of pathological findings the more complex non-volitional and finally invasive procedures are applied^{4,5,6}. Table 1 illustrates the non-pathological threshold values for each particular test and reflects the current consensus of (inter-)national guidelines and current studies^{2,4,5,6,7,8}.

Table 1. Threshold values (non-pathological) for respiratory muscle testing.

	Female threshold value (non-pathological)	Male threshold value (non-pathological)
[All kPa]		
P_{0.1}	<0.3	<0.3
PI_{max1.0} RV	>6.0	>7.0
PI_{maxpeak} RV	>7.0	>8.0
PE_{max}	>7.0	>10.0
P_{0.1}/ PI_{max1.0}	<4.5	<4.5
P_{0.1}/ PI_{max-}	<2.0	<2.0
P_{0.1}*t_i/V_T	<0.5	<0.5
S_n P_{na}	>6.0	>7.0
S_n P_{di}	>8.0	>10.0
Tw P_{mo}	>1.0	>1.0
Tw P_{di}	>1.8	>1.8

P_{0.1}: mouth occlusion pressure at 0.1 s inspiration;

PI_{max1.0} / PI_{maxpeak} RV: maximal inspiratory mouth occlusion pressure (residual volume, hold over 1 s / peak value);

PEmax: maximal expiratory mouth occlusion pressure;

P_{0.1}/PImax: respiratory capacity;

P_{0.1}*t_i/V_T: specific inspiratory impedance;

Sn Pna: sniff nasal pressure;

Sn Pdi: sniff transdiaphragmatic pressure; /

Tw Pmo: twitch mouth pressure;

Tw Pdi: twitch transdiaphragmatic pressure

Table 2 summarizes the characteristics of each particular respiratory muscle test. Beyond the methods which assess respiratory muscle strength, and are discussed in this review, there are several means to assess fatigue and/or endurance of the respiratory pump (e.g. electromyogram or muscular relaxation time). However, general clinical acceptance of these methods is poor due to their high complexity.

Volitional tests on respiratory muscle function

1. Mouth occlusion pressure at 0.1s of

inspiration: P_{0.1}

The P_{0.1} reflects an indirect measure of the central respiratory drive. This measure is influenced by several factors (e.g. tidal volume) due to its dependency on pressure generation and transmission. Misjudgment of the central respiratory drive can result if this linkage is disrupted (e.g. muscle relaxants: maximal central respiratory drive and zero P_{0.1}).

In practice, airways are occluded at the mouth (≥120 ms) during quiet breathing and P_{0.1} is registered after 100ms. To exclude adaptation of the ventilatory pattern prior to P_{0.1} registration the occlusion is applied without notifying the patient in advance. At least 2 breaths separate each consecutive assessment of P_{0.1} and the median of 5 congruent measurements is registered^{2,5}.

2. Maximal inspiratory/expiratory mouth occlusion pressure: PImax/PEmax

PImax and PEmax currently reflect the most widely applied methods for assessing global respiratory muscle strength. Both methods are independent from pathological resistance/compliance changes due to the missing changes in lung volume (isometric contraction). It is important to avoid pure static pressure development due to the risk of inconsistent glottis closure. A standardized leakage (canula with 4 cm in length and internal diameter of 1 mm) ensures a minimal airflow at all times.

PImax can be assessed at functional residual capacity (FRC) or residual volume (RV) without (FRC) / with (RV) additive thoracic retraction forces. PImax is registered as peak-value (PImax_{peak}) or plateau-value over 1s (PImax_{1.0}, more widely-used)^{2,5,7}. PEmax is assessed as peak-value at total lung capacity (TLC)

Table 2. Respiratory muscle testing: method characteristics. P_{0.1}: mouth occlusion pressure at 0.1 s inspiration;

	Non-volitional	Invasive	Technical Complexity	Reproducibility	Variance of Normal Values	Data Basis of Normal Values
P _{0.1}	—	—	—	-	↔	excellent
PImax	—	—	↔	↔	-	excellent
PEmax	—	—	↔	—	-	sufficient
P _{0.1} /PImax	—	—	↔	↔	-	sufficient
P _{0.1} *t _i /V _T	—	—	—	-	↔	insufficient
Sn Pna	—	—	↔	--	—	sufficient
Sn Pdi	—	yes	--	--	—	sufficient
Tw Pmo	yes	—	-	--	—	insufficient
Tw Pdi	yes	yes	--	--	—	insufficient

PImax: maximal inspiratory mouth occlusion pressure;

PEmax: maximal expiratory mouth occlusion pressure;

P_{0.1}/PImax: respiratory capacity;

P_{0.1}*t_i/V_T: specific inspiratory impedance;

Sn Pna: sniff nasal pressure;

Sn Pdi: sniff transdiaphragmatic pressure;

Tw Pmo: twitch mouth pressure;

Tw Pdi: twitch transdiaphragmatic pressure.

analog to P_{lmax}. The pressure is generated solely by the expiratory muscles and it has to be taken care that there is no use of buccal muscles. As a result from the positive pressure gradient from the mouth to the mouth-piece leakage is a common problem in P_Emax assessment.

In practice, P_{lmax} (from RV) and P_Emax (from TLC) are measured at a volitional maximal inspiratory/ expiratory effort with occluded airways. It is essential that the examiner motivates the patient to achieve truly maximal efforts. The maximal value out of seven trials is registered. Each consecutive assessment of P_{lmax}/P_Emax is separated by at least 30 s. The test series should not end with the highest achieved value and differences between the two highest values should be $\leq 10\%$ ^{2,4,5,7}.

3. Respiratory capacity: P_{0.1}/P_{lmax}

The ratio of P_{0.1}/P_{lmax} is referred to as the respiratory capacity and reflects the momentary operational demands of the inspiratory muscles. Inspiratory muscle weakness with false-low P_{0.1} values results in the risk to overlook an increase in the central respiratory drive. This risk is minimised by considering the respiratory capacity. P_{0.1}/P_{lmax} is expressed as % where higher values represent reduced capacity. Values above a defined threshold (app. 20-25 %) indicate the risk of ventilatory failure².

4. Specific inspiratory impedance: P_{0.1}*t_i/V_T

Physically, this value represents a resistance. Here, P_{0.1} reflects the pressure needed to achieve a certain inspiratory flow (V_T/t_i). P_{0.1}*t_i/V_T reflects the load which is momentarily imposed on the inspiratory muscles. The higher the impedance (i.e. the pressure needed to achieve a certain inspiratory flow), the higher the load imposed on the inspiratory muscles. P_{0.1}*t_i/V_T considers the level of momentary ventilation which sole consideration of P_{0.1} does not.

5. Sniff pressures: Sn P

In contrast to all aforementioned static airway-occluded methods Sn P represent dynamically-assessed measures. Patients perform short, maximal inspiratory efforts through the nose. The assessment of Sn P is better tolerated than static respiratory efforts. In addition, the variance is smaller and the reproducibility higher compared to P_{lmax}.

5.1. Nasal sniff pressure: Sn P_{na}

Son P_{na} reflects an important non-invasive parameter for assessing inspiratory muscle strength. It has to be considered that impaired pressure transduction from the pleura (e.g. end-stage COPD) might underestimate inspiratory pressure generation.

5.2. Transdiaphragmatic sniff pressure: Sn P_{di}

The invasive assessment of Sn P_{di} achieves an increase in diaphragmatic specificity, independent from pleural pressure transduction. Sn P_{di} is assessed by transnasal application of enteric balloon catheters and is calculated as the difference between esophageal and gastric pressure (q.v. *twitch pressures*).

In practice, Sn P are registered from FRC during a maximal, short inspiration (lasting <0.5 s) through the nose with the mouth closed. The examiner motivates the patient to achieve truly maximal efforts. Seven trials are performed and the maximal value is registered. Each consecutive measurement of Sn P is separated by at least 30 s (q.v. P_{lmax}/P_Emax). The test series should not end with the highest achieved value and differences between the two highest values should be $\leq 10\%$ ^{4,5}.

Non-volitional tests on respiratory muscle function

All of the methods discussed above have one substantial disadvantage in common: their dependency on the patient's motivation and cooperation. Therefore, low values cannot simply be attributed to respiratory muscle impairment but rather might reflect false-low values caused by insufficient maximal effort. Methods independent from the patient's cooperation and motivation have to be applied to objectify these results.

1. Twitch pressures: Tw P

The current gold-standard technique in (non-volitional) assessment of respiratory muscle strength is represented by pressure registration during stimulation of the phrenic nerves. Former electric stimulation has been almost entirely replaced by magnetic nerve stimulation which is painless and reliable. Here, short-term, high-energy magnetic fields induce a current over the phrenic nerves, resulting in a singular diaphragmatic contraction. For safety reasons, all patients with cardiac pacemakers or other implanted electrical devices or metal parts have to be excluded from this technique. Bilateral anterior magnetic phrenic nerve stimulation (BAMPS) has proven to be the most reliable method achieving supramaximality^{8,9,10}.

Tw P are registered close to FRC due to the linear relationship between lung volume and Tw P^{8,10}. A standardized resting period of 15-20 min should precede Tw P assessment to avoid excessive demands on the diaphragm (e.g. caused by physical exercise). Consecutive measurements are separated by at least 30 s. Figure 2 illustrates exemplary pressure-time curves for Tw P.

2. Twitch mouth pressure: Tw P_{mo}

Non-invasive Tw P_{mo} reliably assesses respiratory muscle strength if the pressure transduction from the pleura to the mouth is not impaired. A trigger mechanism (a certain flow or pressure value at the leakage, q.v. P_{lmax}/P_Emax) avoids inconsistent glottic closure. An inspiratory pressure trigger achieves the narrowest limits of agreement between Tw P_{mo} and esophageal (= pleural) pressure^{8,10}.

3. Transdiaphragmatic twitch pressure: Tw P_{di}

As an invasive procedure Tw P_{di} is assessed following transnasal balloon catheter placement^{4,5,8}. Tw P_{di} is calculated as point-to-point subtraction of gastric (Tw P_{ga}, $\approx 1/3$ Tw P_{di}) from esophageal twitch pressure (Tw P_{es}, $\approx 2/3$ Tw P_{di}). The standardized balloon

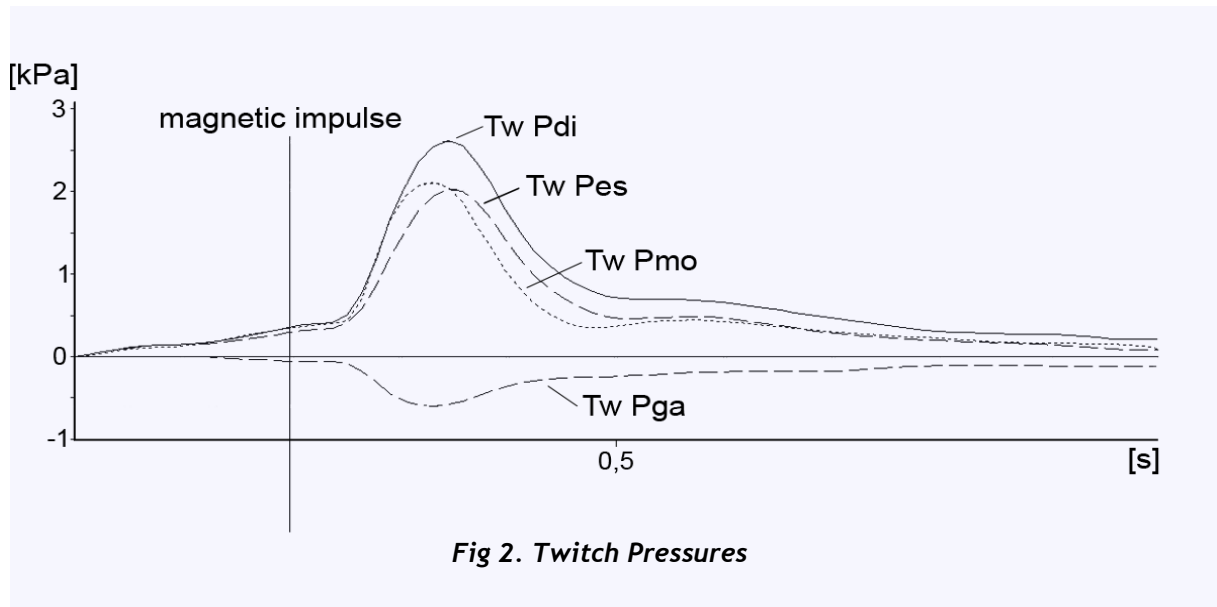


Fig 2. Twitch Pressures

catheter placement is as follows: both balloons are initially placed in the stomach. While pulling back the catheter a pressure reversal is seen at the proximal balloon at the esophageal-gastric passage. From there the catheter is pulled back another 5-10 cm and then safely fixed. Verification of correct catheter position is achieved by sniff maneuvers (q.v. *sniff pressures*).⁵ As standard the balloons usually contain 1.0 (esophageal) and 2.0 (gastric) ml of air depending on the pressure-tension relationship of the balloons. No trigger is needed for sole Tw Pdi registration since glottic closure does not influence pressure transduction from the pleura to the esophagus or stomach. In contrast to all aforementioned parameters which represent maximal volitional efforts, Tw P are registered as the mean of five trials⁵.

References

1. Criée CP, Laier-Groeneveld G. The respiratory pump: respiratory muscles and intermittent ventilation. Stuttgart: Thieme, 1995.
2. Criée CP. Recommendations of the German Airway League (Deutsche Atemwegsliga) for the determination of inspiratory muscle function. *Pneumologie*. 2003; 57: 98-100.
3. Thews G, "Lung breathing" in Schmidt RF, Thews G (eds.) *Human Physiology*. Berlin: Springer, 1977: 565-591
4. Moxham J. *Respiratory Muscles* in Hughes JMB, Pride NB (eds.) *Lung Function Tests*. London: WB Saunders, 1999: 57-72
5. ATS/ERS. Statement on respiratory muscle testing. *Am J Respir Crit Care Med*. 2002; 166: 518-624.
6. Polkey MI, Green M, Moxham J. Measurement of respiratory muscle strength. *Thorax*. 1995; 50: 1131-1135.
7. Windisch W, Hennings E, Sorichter S, et al.,

Peak or plateau maximal inspiratory mouth pressure: which is best? *Eur Respir J*. 2004; 23: 708-713.

8. Kabitz HJ, Walker D, Walterspacher S, et al. Controlled twitch mouth pressure reliably predicts twitch esophageal pressure. *Respir Physiol Neurobiol*. 2007; 156: 276-282.

9. Mills GH, Kyroussis D, Hamnegard CH, et al. Bilateral magnetic stimulation of the phrenic nerves from an anterolateral approach. *Am J Respir Crit Care Med*. 1996; 154: 1099-1105.

10. Windisch W, Kabitz HJ, Sorichter S. Influence of different trigger techniques on twitch mouth pressure during bilateral anterior magnetic phrenic nerve stimulation. *Chest*. 2005; 128: 190-195.

Correspondence

Hans-Joachim Kabitz, MD
 Department of Pneumology
 University Hospital of Freiburg
 Killianstrasse 5
 79106 Freiburg, Germany
 Tel: +49 761 270-3706 Fax: +49 761 270-3704
 E-mail: hans-joachim.kabitz@uniklinik-freiburg.de
