Measurement of respiratory muscle strength

Why must the chest physician become familiar with assessment of the respiratory muscles? Firstly, because dyspnoea in patients in whom no pulmonary cause can be detected may be due to respiratory muscle weakness.[1 2] Even moderately severe muscle weakness may be difficult to detect clinically[3] and, indeed, it is possible to have total paralysis of the diaphragm without life threatening consequences.[4] Secondly, because patients with clearly documented generalised neuromuscular disease usually also have respiratory muscle weakness[2] and, for selected cases, treatment in the form of non-invasive ventilation is indicated.[5] Finally, there has recently been increased awareness that respiratory muscle weakness can be a compounding factor in other disease processes such as malnutrition[6] and steroid therapy.[7] For all of these reasons it is important for respiratory physicians to initiate and to be able to interpret simple tests of respiratory muscle function. For most patients the suspicion of clinically important respiratory muscle weakness may be confirmed or excluded by simple tests that can be performed in the general hospital setting without the purchase of expensive equipment, but in some patients complex tests in a specialised laboratory are necessary (fig 1). In this editorial the current techniques to assess respiratory muscle strength are reviewed with reference to these two different environments. Respiratory muscle fatigue will not be addressed, but has been reviewed recently.[8 9]

Bedside and clinic tests

HISTORY AND EXAMINATION
History and examination may confirm features of the many conditions, both neurogenic and myopathic, that can cause respiratory muscle weakness. In generalised neuromuscular disorders it is unusual for the respiratory muscles to be spared. Wasting and fasciculation of the limb and accessory muscles can be striking as, for example, in motor neurone disease. Severe generalised respiratory muscle weakness causes breathlessness and tachypnoea. Breathlessness when sitting or standing in water, or when supine, is a specific feature of severe diaphragm weakness. When generalised weakness becomes sufficiently severe nocturnal hypoventilation disrupts sleep, causing daytime somnolence and impaired intellectual function.[10] Eventually ventilatory failure and cor pulmonale develop. Weakness of bulbar and expiratory muscles impair cough and so predispose to aspiration and pneumonia.

On examination the characteristic finding of profound bilateral diaphragm weakness or paralysis is paradoxical inward inspiratory abdominal motion; this is more obvious with the patient supine.[4] As a consequence of poor diaphragm contractility accessory muscle activity greatly increases when ventilation is increased and, when upright, the abdominal muscles may be visibly recruited during expiration, serving to elevate the diaphragm and allowing subsequent gravitationally assisted descent during inspiration.[11] These clinical features are seldom present until diaphragm strength is reduced to about a quarter of normal; thus, substantial diaphragm weakness can be overlooked on clinical examination.[2]

IMAGING
In hemidiaphragm paralysis an elevated hemidiaphragm may be visible on chest radiography. With substantial bilateral diaphragm weakness the chest radiograph may show elevated hemidiaphragms, but can appear relatively normal.[4] Similarly, a cephalad movement of the diaphragm is commonly observed on fluoroscopy during inspiratory manoeuvres but this test has the twin disadvantages of both a significant false positive rate[12] and that little information about the degree of diaphragm weakness is provided. The best manoeuvre is a short sharp submaximal sniff. In bilateral paralysis pre-inspiratory elevation of the diaphragm by the abdominal muscles may restore the normal caudal motion giving rise to false negatives.[11] Hemidiaphragm movement may also be semiquantitatively assessed using ultrasound which has the advantage of avoiding irradiation.[13]

LUNG FUNCTION
On lung function testing the characteristic abnormality of inspiratory muscle weakness is a low vital capacity (VC) with a reduced total lung capacity (TLC) and preserved residual volume (RV). Carbon monoxide transfer is reduced, but is normal or raised when adjusted for volume,
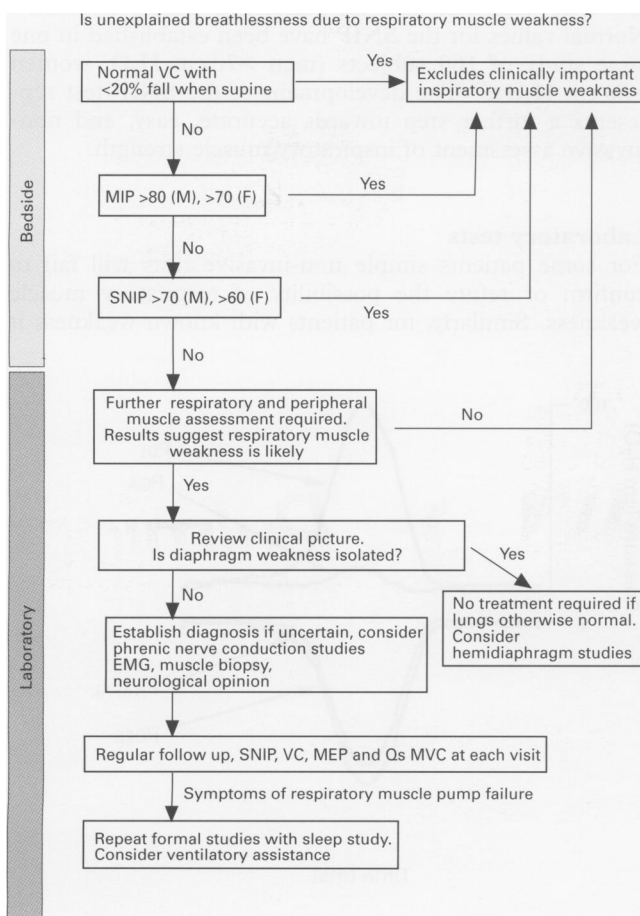

Figure 1   Algorithm for the approach to assessment of the respiratory muscles. An incremental approach is used for most patients. For the remainder, comprehensive specialist tests are indicated. VC = vital capacity; MIP = maximum inspiratory pressure; MEP = maximum expiratory pressure; SNIP = sniff nasal inspiratory pressure; Qs = quadriceps; MVC = maximum voluntary contraction force.

and this serves to distinguish respiratory muscle weakness from alveolar disorders such as pulmonary fibrosis.[2]

Measurement of VC is of great value. An entirely normal VC makes significant respiratory muscle weakness unlikely. In subjects with diaphragm weakness the VC falls when the patient is supine, though this fall must exceed 25% to be unequivocally abnormal.[14] Thus, a normal supine VC excludes clinically relevant inspiratory muscle weakness. In longstanding weakness the VC may fall further because of reduced chest wall and lung compliance, possibly associated with microatelectasis,[15] though this in itself does not detract from the diagnostic value of the test. The VC is of value for frequent monitoring of patients at risk of rapidly progressive muscle weakness or paralysis, the best clinical example being Guillain-Barré syndrome.[16] However, measurement of VC is volitional and relies on patient motivation and ability. Use of an anaesthetic style facemask may help if disease precludes the use of a mouthpiece. Apart from depending on effort and cooperation by the patient, a major limitation of VC is that it is reduced by factors other than weakness: a low VC can therefore be non-specific and non-diagnostic.

Overnight pulse oximetry, performed as an inpatient or in the patient's home, can, if normal, provide evidence that any weakness is not sufficiently severe to cause overt ventilatory failure. Conversely, the demonstration of nocturnal hypoventilation signifies that respiratory muscle weakness is sufficiently severe to lead to ventilatory failure. Sleep studies may therefore be of value in the assessment of the load/capacity balance in such patients; substantial nocturnal desaturation does not occur until global respiratory muscle strength is reduced to below one third of normal in patients with neuromuscular disease alone, but occurs earlier if there is coexisting respiratory disease increasing ventilatory load (see below).

MOUTH PRESSURES

The most widely applied tests of global inspiratory and expiratory muscle strength are the static inspiratory and expiratory pressures measured at the mouth (MIP and MEP). These tests have the advantage that they are non-invasive and normal values have been established in quite large series.[17-21] Conventionally, MIP is measured from RV although this has the theoretical disadvantage that recoil of the chest wall contributes to the value obtained. In practice patients find the manoeuvre easier from RV than functional residual capacity (FRC) and, for the purpose of screening out patients who do not have inspiratory muscle weakness, the difference is not important. Portable inexpensive mouth pressure meters allow immediate measurement of the MIP and MEP at the bedside or in the clinic.[22] As with the VC a high MIP (say >80 cm H_2O) is of great value in excluding clinically important inspiratory muscle weakness.

Whilst a high MIP, by excluding inspiratory muscle weakness, is a valuable piece of clinical information, a lower value is frequently difficult to interpret. One problem with static pressures is that they are volitional; thus, for the result to be a true measure of strength the subject must make a maximal contraction. If three equal "maximum" efforts are obtained then it is conventionally assumed that the subject is making a maximal effort, but it has recently been shown that reproducibility does not ensure maximality.[23] To assess the degree of voluntary effort it is possible to stimulate electrically the nerves supplying the diaphragm during the contraction; if no additional transdiaphragmatic pressure (PDI) is observed then the contraction is considered to be maximal (the twitch occlusion technique). Using this technique maximal activation of the

diaphragm during the MIP manoeuvre has been demonstrated in some, but not all, normal subjects[24 25] and patients.[26 27] Values tend to be higher with a tube mouthpiece, but patients find this difficult to use so a flanged type is the norm.[28] Patients with neuromuscular disease involving the orofacial muscles may have difficulty in forming an airtight seal around either type of mouthpiece, and this will lead to an underestimation of static pressures. With the development of new tests of inspiratory muscle strength (see below) the MIP may not be the most suitable measurement when a reproducible quantitative assessment is required as, for example, in studies of respiratory muscle training. The MEP is subject to the same concerns as the MIP but, unlike the MIP, there are no alternative tests currently available outside specialised laboratories.

NASAL PRESSURES

The sniff is a natural manoeuvre which many patients find easier to perform than static efforts.[29] In normal subjects the pressure measured in the oesophagus during a sniff is closely related to that in the mouth, nasopharynx, and nose (fig 2).[30-32] Thus, in both normal subjects and patients with inspiratory muscle weakness the sniff nasal inspiratory pressure (SNIP) provides a reasonable estimate of inspiratory muscle strength.[32] In patients with chronic obstructive pulmonary disease (COPD) the SNIP, unlike the MIP, underestimates strength[33]; this is expected because the sniff is a short manoeuvre and the transmission of the pressure response from the oesophagus to mouth and nose is dampened in COPD.[34] The SNIP can be particularly helpful when deciding whether to pursue the finding of a low MIP and can also be performed at the bedside.[35] Normal values for the SNIP have been established in one large study of 160 subjects (men >70 cm H_2O, women >60 cm H_2O).[36] The development of the SNIP test represents a further step towards accurate, easy, and non-invasive assessment of inspiratory muscle strength.

Laboratory tests

For some patients simple non-invasive tests will fail to confirm or refute the possibility of respiratory muscle weakness. Similarly, for patients with known weakness it
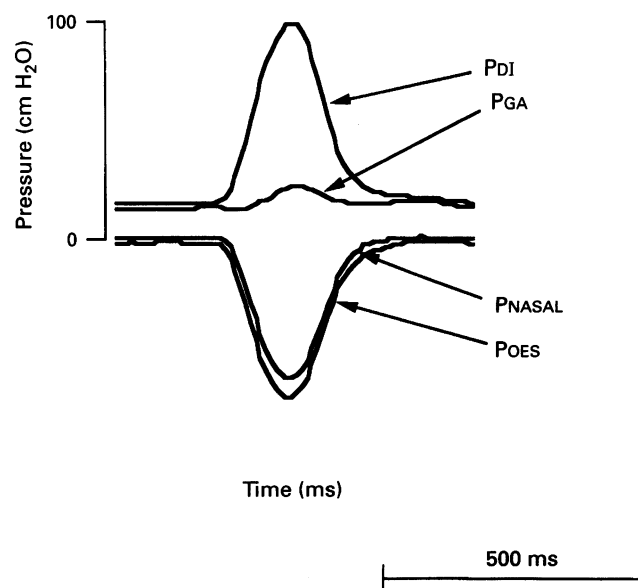

Figure 2 Pressures produced by a sniff in a normal subject. PNASAL is observed to follow POES closely. PDI = transdiaphragmatic pressure; PGA = gastric pressure; POES = oesophageal pressure.

is sometimes important to make a precise estimation of the weakness in order to make decisions about management. For these patients formal assessment of respiratory muscle strength is required, and this assessment should include non-volitional tests. Placement of oesophageal and gastric balloons using topical anaesthesia allows measurement of oesophageal, gastric, and transdiaphragmatic pressure, and also dynamic compliance. We have made such measurements in many hundreds of patients in our laboratories over the last 20 years, achieving successful placement of balloons in over 95% of patients.

SNIFF PDI AND POES

Amost all patients are able to make maximum sniff efforts. The sniff is performed from FRC with no noseclip. When thus performed the volume increase is small, about 500 ml,[37] and diaphragm contraction is therefore relatively isometric. In normal subjects sniff transdiaphragmatic pressure (sniff PDI) has a narrower normal range and a better between day coefficient of variation than the MIP manoeuvre.[29] In patients about one sixth have a low MIP but a normal sniff oesophageal pressure (sniff POES normal values, men >80 cm H$_2$O, women >70 cm H$_2$O). Since the diaphragm is normally the most important single muscle of inspiration it is not surprising that sniff POES, a measure of global inspiratory muscle strength, is closely related to sniff PDI, a specific measure of diaphragm strength. Thus, diagnostically useful information about inspiratory muscle strength and, by inference, diaphragm strength may be obtained with a single oesophageal catheter/transducer system as routinely used for the measurement of lung compliance.[38] In clinical practice sniff POES and sniff PDI are the most accurate and reproducible volitional tests currently available to assess global inspiratory and diaphragmatic strength.

NON-VOLITIONAL TESTS: PHRENIC NERVE STIMULATION
Electrical stimulation
Although sniff pressures are considerably more accurate and reproducible than MIP, the sniff manoeuvre does require the understanding and cooperation of the patient. Electrical phrenic nerve stimulation (ES) in the neck and the measurement of twitch PDI has the advantage of eliminating variation due to patient motivation and also allows measurement of the EMG signal and nerve conduction time (normal (SD) range 7·7 (0·8) ms).[39 40] In isolated fresh mammalian skeletal muscle preparations there is a constant relationship between the force generated by a single twitch and the force generated by a tetanic fusion of contractions, the twitch:tetanus ratio.[41] With electrical phrenic nerve stimulation, when supramaximal, the relationship between twitch PDI and maximum sniff PDI is similar to the twitch: tetanus ratio observed in isolated mammalian muscle.[42] However, precise electrode placement is essential if a truly supramaximal stimulation is to be achieved. To accomplish this repeated stimulations are frequently required and, since electrical stimulation is painful, this limits the extent to which the technique can be used in clinical studies. Patients may find it difficult to relax during electrical phrenic nerve stimulation, thereby causing an increase in twitch tension – the phenomenon of twitch potentiation.[43 44] Nevertheless, bilateral electrical phrenic nerve stimulation has been used to measure twitch transdiaphragmatic pressure in normal subjects[42 45] and patients.[46 47] Perhaps because of the reasons discussed above, the reported normal range is wide (8·8–33 cm H$_2$O) making it diagnostically useful only when there is severe weakness or, when the

result is unequivocally normal (thus excluding weakness), in patients unable or unwilling to perform volitional tests.[48] Hemidiaphragm function may be usefully assessed by unilateral electrical stimulation of the phrenic nerves.[49]

Magnetic stimulation
Many of the problems associated with electrical stimulation have been largely overcome by the introduction of magnetic stimulation of the phrenic nerves. By discharging a magnetic coil it is possible to create a pulsed magnetic field which causes current to flow in nervous tissue within the field which in turn causes muscle to contract.[50 51] Supramaximal bilateral phrenic nerve stimulation may be achieved using a circular coil placed over the cervical phrenic nerve roots.[52 53] The magnetically elicited PDI is slightly greater than the electrical, the difference being due to a larger POES.[53] This is thought to be due to activation of the accessory muscles because of spread of the magnetic field.[52 53] In clinical practice the small difference in PDI with the magnetic technique is seldom important, except that it can give rise to a falsely short phrenic nerve conduction time. Magnetic stimulation, unlike electrical, is painless and it is usually possible to achieve reproducible stimulation without the problem of twitch potentiation. Magnetic stimulation has a higher and better defined lower limit of normal than electrical stimulation, and better correlation with sniff PDI which, in turn, increases its diagnostic sensitivity in patients with moderate diaphragm weakness[54] and allows sequential studies in patients.[55] Stimulation of the phrenic nerves anteriorly with a figure of eight coil allows easy and accurate quantification of hemidiaphragm function[56] and, by using bilateral anterior stimulation, diaphragm function can be studied in supine subjects[57] – for example, those undergoing coronary artery surgery[58] and those in intensive care. For clinical studies it is likely that magnetic phrenic nerve stimulation will largely replace electrical stimulation, and phrenic nerve stimulation will be possible in circumstances not hitherto practical.

NON-INVASIVE ASSESSMENT OF DIAPHRAGM CONTRACTILITY
Just as sniff oesophageal pressure is reflected in the nose, so twitch POES may be assessed at the mouth in both normal subjects[59] and in patients with respiratory muscle weakness.[60] In patients with COPD the equilibration of POES with PMOUTH is slow and the technique is not, in practice, as useful.[61] The combination of easy and painless magnetic stimulation of the phrenic nerves and the measurement of twitch mouth pressure (fig 3) opens the way for non-invasive assessment of diaphragm function. Interestingly, it has recently been reported that force generated during a diaphragmatic twitch may also be quantitatively assessed non-invasively by measuring the sound created by the contracting diaphragm.[62]

ASSESSMENT OF THE LOAD/CAPACITY BALANCE
Isolated diaphragm weakness – and even paralysis – is without life threatening sequelae,[4] which underlines the fact that, for ventilatory failure to occur, load must exceed capacity.[8] Although daytime ventilatory failure is not a feature of isolated bilateral diaphragm paralysis,[4] such patients do have nocturnal desaturation, particularly during rapid eye movement (REM) sleep, and the importance of this has yet to be elucidated.[4 63] In the clinical assessment of respiratory muscle dysfunction consideration of the ventilatory load is of great importance. The likelihood of additional load may be predicted if other investigations
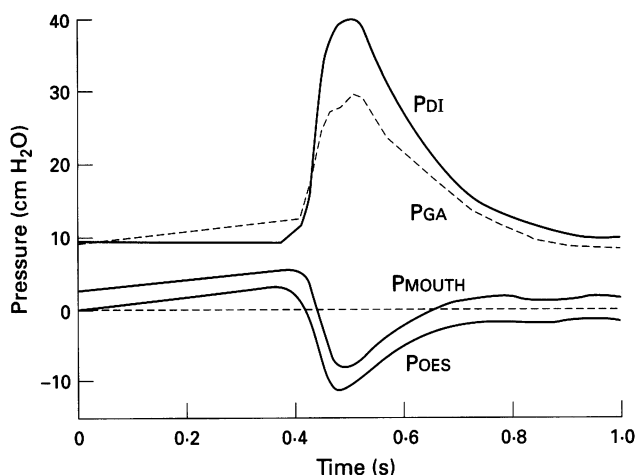
Figure 3 Pressures produced by cervical magnetic stimulation in a normal subject. PMOUTH closely follows oesophageal pressure (POES). PDI = transdiaphragmatic pressure; PGA = gastric pressure. Reproduced with permission from ref 60.

indicate airways obstruction or restrictive lung or chest wall disease; the latter may be suggested by measurement of dynamic compliance and is easy to document with an oesophageal balloon in situ. Severe imbalance of the load/capacity relationship is suggested by nocturnal hypoventilation with compensatory bicarbonate retention. Collapse of the upper airway during sleep may aggravate the situation and is relatively more common in patients with generalised neuromuscular disease.

EXPIRATORY MUSCLE STRENGTH

The only test of expiratory muscle strength generally available is the MEP which, although often useful, has the same limitations as the MIP manoeuvre. In our laboratory we commonly measure gastric pressure both during maximum coughs and maximum whistles (performed on a paediatric peak flow whistle). We believe that PGA obtained in this way is a useful supplement to MEP, although normal values have yet to be formally described. It is also possible to obtain a non-volitional measurement of expiratory muscle strength by administering a magnetic stimulation over the nerve roots at T10. Although this technique is not supramaximal it is, in physiologists at least, highly reproducible.[64]

LIMB MUSCLES

When assessing patients with respiratory muscle weakness it is useful to assess the strength of peripheral skeletal muscles since weakness of these muscles is frequently evident in neuromuscular and systemic disease.[2] Supramaximal electrical stimulation of the small muscles of the hand is possible[65] but is painful and technically difficult. The maximum voluntary contraction force of the quadriceps is a reproducible measure of muscle strength provided the patient is conscious and fully motivated.[66] Electrical stimulation using pads applied to the muscle is not supramaximal and, although useful in research studies of fatigue, is not a good clinical test of weakness. We have recently shown, however, that it is possible to obtain a painless reproducible supramaximal magnetic stimulation of the quadriceps by discharging a figure of eight coil over the femoral nerve in the femoral triangle.[67] This offers the prospect of a complementary non-volitional test of quadriceps strength which may be conveniently undertaken in a respiratory muscle laboratory.

Conclusion

The range of techniques available to assess respiratory muscle weakness has greatly expanded in recent years. Sniff nasal pressure and magnetic twitch PDI are likely to be particularly important advances. How should the clinicians use these techniques? For screening patients with unexplained breathlessness and for diagnosing the presence of weakness a graded approach is best using tests in order of increasing complexity and invasiveness (fig 1); full respiratory muscle assessment will be required for only a few cases. For following patients with progressive neuromuscular problems – for example, motor neurone disease – where repeated measurements are required, simple procedures are most appropriate and the combination of VC and SNIP with MEP and quadriceps maximum voluntary contraction force would be one suitable combination. If a major treatment change – for example, non-invasive ventilation – is planned for such patients, more detailed muscle studies combined with sleep studies may be indicated. There is now no justification for relying on volitional tests alone in studies of fatigue, training and rehabilitation, and in patients unable or unwilling to make maximum voluntary efforts.

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