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Respiratory Muscles: A Review of Old and Newer Concepts *

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Abstract. The function of the respiratory muscles in health and disease is currently receiving increased and long overdue interest. Points of practical as well as theoretical interest are the following:

1. The diaphragm, by far the most important of the respiratory muscles, has unique mechanical and metabolic characteristics which probably represent advantageous adaptations to its function.

2. Both the length-tension properties of the diaphragm and its distinctive curved geometry (i.e. in relation to Laplace's law) are important in the diaphragm's function in human health and disease.

3. Pioneering recent work by Goldman and Mead indicate that in most circumstances the diaphragm moves the rib cage effectively and that the other muscles of respiration usually act to optimize the length-tension conditions of the diaphragm's function.

4. There is mounting evidence that tonic as well as phasic activity of respiratory muscles is a major determinant of lung volume in many circumstances in both health and disease.

5. Fatigue of respiratory muscles is being recognized as an important contributor to respiratory disability and failure, and several methods of recognizing fatigue are being developed.

6. The relief from dyspnea experienced by some severe emphysema patients when they lean forward or lie supine is, we believe, related to the improved length-tension state of the diaphragm which the more comfortable postures favor.

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It has been said that discussing respiration without considering the respiratory muscles is like considering the circulation and not mentioning the heart. Ventilatory failure like cardiac failure is a common and important clinical entity. Cardiac failure results from inability of the myocardium, either through intrinsic weakness or because of prolonged excessive loading, to pump blood to the tissues in adequate amounts. Similarly, ventilatory failure usually develops because the balance between respiratory mechanical impedances and the muscle power to overcome them has tipped in favor of the impedances and against the respiratory muscles. Until recently most of our attention as clinical physiologists had been paid to the abnormal respiratory system impedances rather than to the respiratory muscles. This is understandable since usually the primary problem responsible for respiratory insufficiency and failure and the element susceptible to treatment involves adverse changes in these impedances, i.e., such changes as increased airway resistance and stiff lungs. However, in the past decade or so, the emphasis has shifted somewhat and respiratory muscles have received increased and long overdue emphasis. In this communication, I will begin by reviewing briefly some of the more important established ideas concerning respiratory muscle function. I shall follow this with a consideration of what I believe are some important developments and new concepts in the field of respiratory muscle function. Finally, I shall present the results of two clinical studies from our laboratory and end with speculations about the relationship of respiratory muscle function to the phenomenon of dyspnea, particularly that occurring in obstructive lung disease.

To begin with, recall that the respiratory muscles, although skeletal in type, differ somewhat from other skeletal muscles. This is particularly true of the principal respiratory muscle, the diaphragm. The respiratory muscles 1) must overcome principally resistive and elastic loads rather than inertial loads as is the case with most other muscles, and 2) are under both voluntary and involuntary control and 3) must contract every few seconds for a lifetime and cannot rest for protracted periods as can limb muscles. Because of this latter point, the diaphragm in particular has both physical and metabolic characteristics which in some ways more resemble those of cardiac muscle than of other skeletal muscles [19, 31, 32, 33, 34, 35].

There is general agreement that the diaphragm is by far the most important respiratory muscle. In normal man, it is responsible almost alone for quiet breathing with rib cage muscle contraction probably serving chiefly to stabilize the rib cage and prevent its distortion by diaphragmatic contraction. When body metabolic demands require increased ventilation, inspiratory rib cage and neck muscles (principally external intercostals, scaleni and sternocleidomastoids) act to deepen inspiratory excursions of the rib cage. Expiratory muscle (abdominal muscles and internal intercostals) activity is not regularly seen until the minute ventilation exceeds about 50% of the maximal voluntary ventilation, expiration being passive under most circumstances, even moderate exercise. As we shall see later, the abdominal and accessory muscles also act as fixators or positioning muscles which adjust the configuration of the rib cage and abdomen in such a way as to optimize the efficiency of the diaphragm.

Since the classic 1946 paper of Rahn et al. [28], we have realized that lung volume affected the force and pressure-developing capabilities of the respiratory muscles. Figure 1, drawn from their paper, shows that the inspiratory muscles develop

pressure more effectively at small lung volumes whereas the expiratory muscles develop pressure more effectively at large lung volumes. Rahn et al. explained this on the basis of the well understood force-length characteristics of muscle, reasoning that inspiratory muscles would be overly shortened at large lung volumes and stretched at small lung volumes approaching residual volume. Force-length diagrams for the diaphragm and a typical limb muscle are shown in Fig. 2. This figure derives from the work of Dr. Mi Ja Kim and others in our laboratory [19], and shows that the diaphragm has a broader effective length range than most other skeletal muscles. As can be seen, force generated by muscle contraction is a function of muscle fiber length. Most muscles generate force most efficiently and effectively when they are at their natural resting length in the body, designated the resting in-situ length or l_0. They cease to generate pressure when shortened to about 65% of l_0. The diaphragm appears to generate force at lengths as short as 40% of l_0. Considering the unique function of the diaphragm and its need to generate force over a wide range of fiber lengths (i.e., corresponding to a wide range of lung volumes) we view the diaphragm's unusual length-tension behavior as a useful adaptation to its functional requirements.

Besides the force-length relationship, the other important intrinsic characteristics of muscle is its force-velocity relationship, shown in Fig. 3. The figure illustrates the inverse relationship between velocity of muscle contraction and force generated, corresponding to the load which the muscle can lift. This relationship is appreciated intuitively when we realize that while we can move a light load rapidly, a heavy load can only be moved slowly. The 1960 study of Agostoni and Fenn [1], showed that this relationship was important in the function of the respiratory muscles. They concluded that maximal inspiratory air flow rates were limited by the rate with which the inspiratory muscles convert chemical energy into mechanical energy. Hyatt and Flath [18] several years later confirmed this but showed that maximal expiratory flows were limited by dynamic airway collapse rather than respiratory muscle energetics.

The geometry of the respiratory muscles also has an important effect upon their function, a point best illustrated by a diaphragm. Figure 4 shows the relationship of Laplace's law and the diaphragm's radii of curvature to its effective function. Clear-

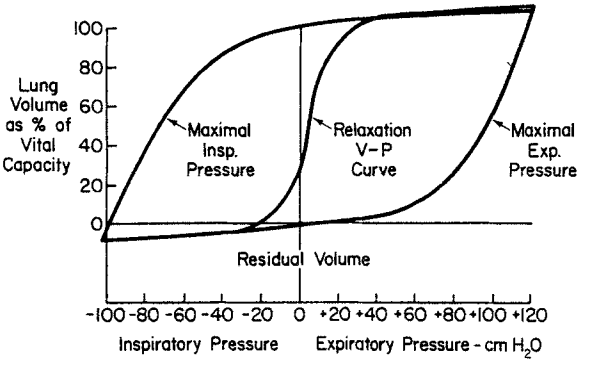

Fig. 1. The volume-pressure diagram of the respiratory system as adapted from Rahn et al. [28]. Since normal respiration requires only a few cm H_2O of pressure, the diagram illustrates the large reserve of respiratory muscle strength which is normally available

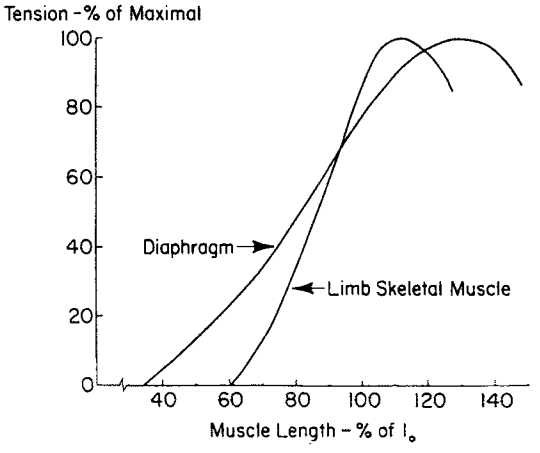

Fig. 2. Length tension diagram of the diaphragm compared to that of a typical limb skeletal muscle, derived from the work of Kim et al. The broader effective length range of the diaphragm is believed to have functional importance

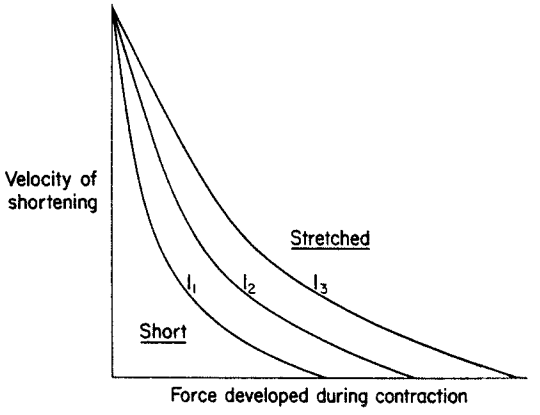

Fig. 3. The force-velocity relationship of skeletal muscle at three different muscle lengths

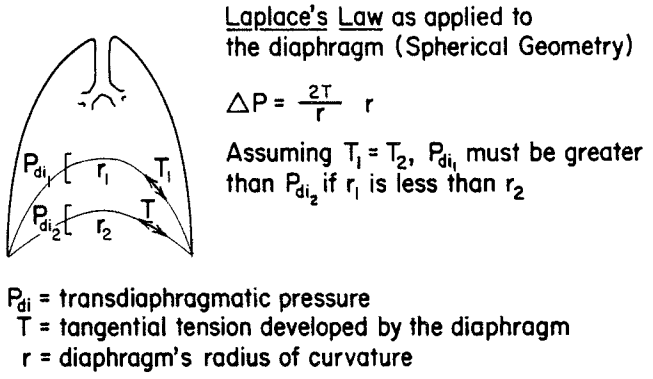

Fig. 4. The functional importance of the diaphragm's geometry. The low flat diaphragm is at a functional disadvantage both because it is shortened (a length tension disadvantage) and because its radius of curvature is increased (a La placian disadvantage)

ly, the flattened diaphragm must function less efficiently than the highly curved and domed diaphragm. This was emphasized by Marshall in 1962 [24]. Recent work of Dr. Kim [19] has suggested that the shape or curvature changes are less important than muscle fiber length changes in the normal dog and by inference, in normal man. There cannot be much question, however, that the low flat diaphragm seen in patients with severe pulmonary emphysema functions ineffectively. We shall speak more of this later.

Although there have been dissenting opinions [15, 16, 17] it has been appreciated since the work of Duchenne [6] over a century ago that diaphragmatic contraction is capable of causing outward and upward inspiratory motion of the rib cage because of the bucket-handle mobility of the lower ribs to which the diaphragm attaches and because the direction of diaphragmatic muscle fibers is parallel to the body's long axis, causing them to exert an upward traction upon the lower ribs. The bucket-handle mobility of the lower ribs converts the upward traction into outward motion. Figure 5 makes the point that the low flattened diaphragm is much less effective in producing outward rib cage motion than the high domed diaphragm. When low enough and flat enough it may, in fact, produce inward (expiratory) motion of the rib cage, a phenomenon well known to clinicians as Hoover's sign [15, 17].

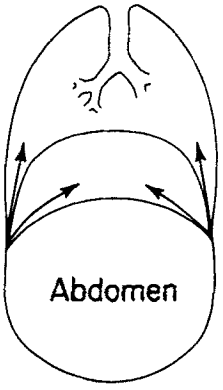

Fig. 5. The diaphragm's action on the rib cage is to pull it upward through its attachments to the lower ribs which move outward as well as upward because of their "bucket handle" mobility. The low flat diaphragm is obviously less able to move the rib cage upward because the pull of its contracting fibers is directed more inward then upward

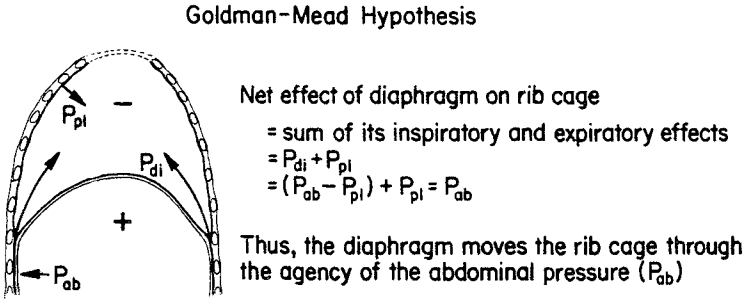

Fig. 6. The Goldman-Mead hypothesis of diaphragm-rib cage interaction which suggests that under most circumstances abdominal pressure is the prime mover of the rib cage. See text for discussion

Recent work of Goldman et al. and Grassino et al. [9, 10, 11] has elucidated further the interactions between diaphragm and rib cage. Their general schema is illustrated in Fig. 6. They point out that the diaphragm when it contracts has both an inspiratory and an expiratory action upon the rib cage. Its *inspiratory* action is represented by the transdiaphragmatic pressure, Pdi, which moves the rib cage upward and outward relative to the abdominal contents. Its *expiratory* action is represented by the negative intrapleural pressure, Ppl, which tends to suck the rib cage in. The net result of opposing inspiratory and expiratory forces on the rib cage is the algebraic sum of the transdiaphragmatic pressure, Pdi and the pleural pressure, Ppl. As the algebra in the figure indicates, this sum turns out to be abdominal pressure, Pab. It appears, then, that the pressure moving the rib cage is abdominal pressure. The area of apposition between the diaphragm and the rib cage also results in the direct application of positive abdominal pressure to the inside of the rib cage tending to move it outward. Ingenious experiments done by Goldman and Mead involving external abdominal compression [9] have strengthened their conclusion that the pressure responsible for moving the rib cage is abdominal pressure.

One can also consider the diaphragm's action on the rib cage in relation to the ease with which the abdominal contents may be moved. If the abdomen is compliant and easily displaced (i.e., the abdominal muscles relaxed), the dome of the diaphragm is displaced downward and diaphragmatic contraction raises the rib cage very little. In this circumstance abdominal pressure would rise little if any. On the other hand, if the anterior and lateral abdominal walls are stiffened by muscle contraction and do not move out of the way when the diaphragm contracts, the abdominal contents serves as an immovable fulcrum for the diaphragm to contract against and around, and the rib cage rises as the diaphragm contracts. In this circumstance abdominal pressure rises considerably. From this illustration it may perhaps be more easily seen why abdominal pressure increases in proportion to the extent to which the diaphragm moves the rib cage upward.

It should also be evident from this illustration that abdominal compliance and the agency through which it may be altered, the abdominal muscles, can influence what the diaphragm does to the rib cage. It should also be clear that abdominal muscle contraction may stretch the diaphragm, improving its force-length state and increasing the effectiveness of diaphragmatic function. Grimby et al. [12] have shown during exercise and CO_2 breathing requiring greater tidal volumes, that the abdomen's anteroposterior diameter becomes less owing to abdominal muscle contraction and that the diaphragm is stretched to a more efficient functional range on its force-length curve. Figure 7 explains by use of the diaphragm's length-tension diagram how optimization of diaphragmatic function works.

Could lack of the ability to optimize diaphragmatic function be a factor contributing to respiratory failure? There is suggestive evidence that it may. Dr. Lopata and his coworkers at the University of Illinois [20] have noted that several patients with the obesity hypoventilation syndrome failed to decrease their abdominal volumes during CO_2 breathing, that is, they apparently failed to optimize their diaphragmatic function. One of these patients showed reversal of this phenomenon with weight reduction. It should also be clear that patients with severe hyperinflation and air trapping owing to severe emphysema have lost most of their ability to optimize diaphragmatic function because they cannot alter lung volume and thora-

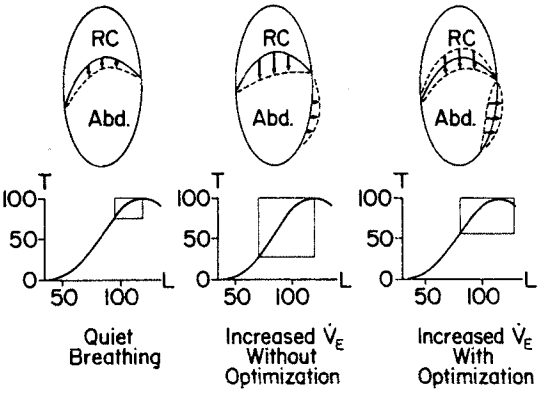

Fig. 7. Optimization of diaphragmatic function through the action of the abdominal muscles. The graphs in the lower portion of the figure represent length (L)-tension (T) diagrams of the diaphragm, and the rectangles on these curves represent the functional range over which the diaphragm is functioning at the indicated level of ventilation. See text for discussion

coabdominal configuration nearly to the extent possible in normal subjects. This surely must be an important factor in the genesis of respiratory muscle fatigue and failure in such patients.

The question of respiratory muscle tone and tonic contractions (as compared to phasic contractions) of respiratory muscles has recently received attention, particularly by A. C. Bryan and his coworkers at Toronto [27]. While phasic contractions are the recurrent contractions responsible for inspiration and expiration, tonic contractions are generally slower and steadier and alter the baseline length of the muscle between phasic contractions. Tonic contraction of respiratory muscles is clearly capable of altering the resting lung volume or FRC. Bryan and his associates have shown in both infants and adults that inspiratory muscle tonic activity present during quiet sleep is significantly reduced during REM sleep. (Parenthetically, it is well known that suppressed muscle activity and depressed reflexes generally characterized REM sleep). In confirmation of this, Henderson-Smart and Read [14] have shown that the FRC of infants falls by 30% with the establishment of REM sleep as compared to quiet slow wave sleep. Bryan and coworkers have also shown that certain anesthetic agents such as halothane also suppress tonic activity in the diaphragm [27]. All of this indicates that the state of inspiratory muscle tone is an important determinant of the FRC, certainly in infants and very possibly in adults as well. This represents a revision of the accepted concept that the FRC is determined by an equilibrium of passive elastic forces between lung, pulling inward, and the chest cage, pulling outward. Finally, the Toronto group have shown in normals and in patients with cystic fibrosis that the reduction in FRC occurring with REM sleep is responsible in part for the significant decrease in arterial oxygen saturation seen in this stage of sleep in many cystic fibrosis patients [26]. This mechanism probably is important in the increased nocturnal hypoxemia seen in many patients with obstructive lung disease and sleep apnea syndromes.

Another consideration of great potential clinical importance is respiratory muscle fatigue. Clearly respiratory muscle fatigue and exhaustion must have a great deal to do with respiratory failure. Recent papers by Gross et al. [13], by Schweitzer et al. [37], and by J. B. Andersen and coworkers from Copenhagen [2] have looked into methods by which it may be detected and quantitated and how the respiratory system deals with respiratory muscle fatigue. Gross et al. and Schweitzer et al. have

applied to the respiratory field the fact, long known to muscle physiologists, that the distribution of frequencies in a muscle's electromyogram shift downward toward lower frequencies with the approach and onset of fatigue. Frequency spectral analysis of EMG's is accomplished by Fourier analysis which may now be done electronically by either digital or analog methods. They have found in animals and man that the EMG frequency spectrum of the diaphragm is indeed shifted downward toward lower frequencies with fatigue. Andersen and coworkers have applied this method together with the measurement of thoracoabdominal motion with magnetometers to the detection of respiratory muscle fatigue in patients being weaned from mechanical ventilators. In their studies, EMG frequency shift proved to be the earliest sign of respiratory muscle fatigue, preceding incoordination of respiratory muscles as signalled by irregularities in the pattern of thoracoabdominal motion. Both of these phenomena were discernible well before the ultimate evidence of fatigue occurred, namely apnea. These latter investigators incidentally found that intermittent mandatory ventilation was effective in delaying or preventing fatigue during the weaning process. A final intriguing recent finding of Macklem and coworkers is that as fatigue approaches, respiratory muscle groups share the stress, trading off and relieving one another in cyclic fashion [36].

Next, I shall turn to recent work from our laboratory. In these studies I am much indebted to the contributions of Drs. Walter Druz, Norma Goldberg, Howard Fishman, Terry Moisan, Mark Wicks, and John Foster. The first work concerns the function of the isolated paced human diaphragm in high quadriplegics [5] and the second looks at the response of the respiratory muscles to changes in body position in severe emphysema [25].

Electrophrenic pacing in the high (C_1) quadriplegic [7, 8] allows one the unique opportunity of studying the diaphragm working alone and unaided by other respiratory muscles and with its neurogenic excitation held perfectly constant and unmodified by reflexes. Figure 8 demonstrates that the major action of the unaided diaphragm upon the rib cage is to produce outward motion of the lower lateral ribs, the so called bucket handle motion. Note that no positive pump handle motion is produced, that is, there is no outward AP displacement of the rib cage; quite to the contrary, the anteroposterior diameter of the rib cage decreases with diaphragmatic contraction. The fact that the anterior and upper lateral aspects of the rib cage are pulled inward by diaphragmatic contraction in contrast to the normal outward displacement emphasizes the importance of the rib cage muscles which function as fixators and stabilizers of the rib cage to prevent such paradoxical motion. Figure 9 shows that the length tension-characteristics of the diaphragm are important even over the physiologic range of volumes. Note that with a modest increase in FRC from its supine level, obtained by head-up tilting, the tidal volume resulting from identical amounts of phrenic stimulation falls to half its supine value. Figure 10 shows the same sort of phenomenon, i.e., dependency of diaphragmatic function upon lung volume, this time measuring 2 pressures, transdiaphragmatic and airway, as lung volume is increased by measured amounts. Both pressures decreased significantly with increasing lung volume indicating that the diaphragm's effectiveness as a pressure generator deteriorates as lung volume increases. These data clearly indicate that neurogenic mechanisms must come to the aid of the intrinsic muscle mechanisms to compensate for changes in the diaphragm's length-tension state and to help it to overcome increased respiratory loads.

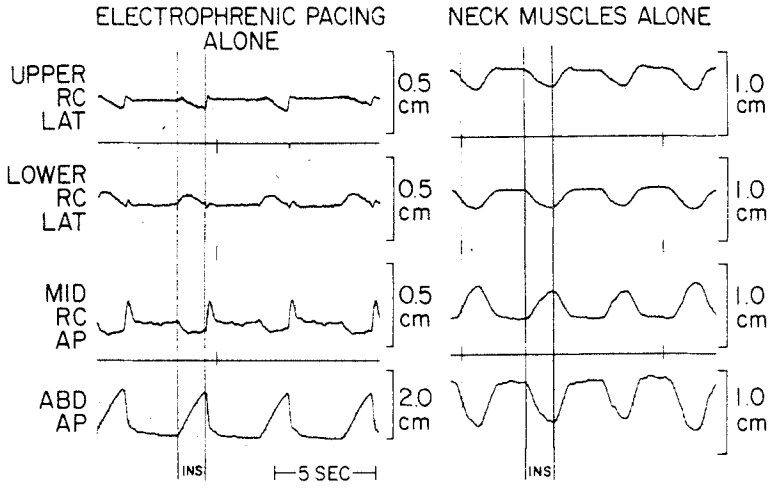

Fig. 8. Magnetometer tracings of throacoabdominal motion in a C-1 quadriplegic patient. The top two tracings represent changes in the lateral diameters of the upper and lower rib cage. The lower two tracings represent changes in the anteroposterior diameters of the mid rib cage and mid abdomen. During electrophrenic pacing (left panel) only the diaphragm is functioning and it is producing pure "bucket handle" motion. When neck muscles alone are functioning, pure "pump handle" motion is produced with sucking in of the abdomen and of the lateral aspects of the rib cage

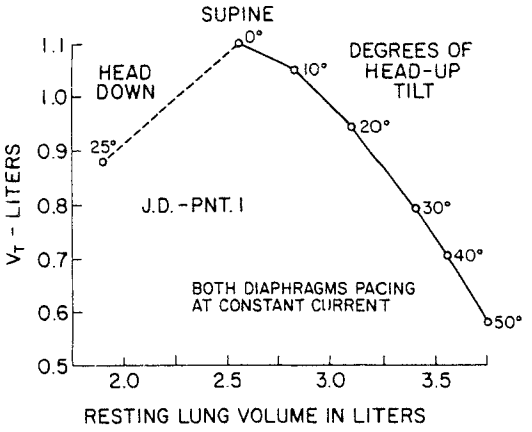

Fig. 9. The effects of changing the FRC (by body tilting) upon the tidal volume during constant bilateral diaphragmatic pacing. Shortening the diaphragm by head up tilting (increasing the FRC) reduces diaphragmatic effectiveness and decreases tidal volume

Severe emphysema represents the ultimate clinical example of the diaphragm at a severe mechanical or length-tension disadvantage. Figure 11 shows actual inversion of the diaphragm's curvature in a severely emphysematous patient. Some years ago we described thoracoabdominal motion as measured by respiratory magnetometers in a number of patients with severe obstructive lung disease [38]. Figure 12 shows a tracing of such measurements in one such patient who was severely hyperinflated. Note that during inspiration both anteroposterior and lateral abdominal motion is inward, whereas rib cage motion is outward. Note also that this abnormal motion pattern is more striking in the upright position than in the supine position. These

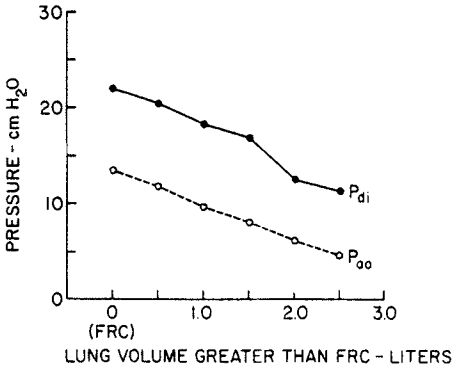

Fig. 10. Transdiaphragmatic pressure and airway pressure generated by the paced diaphragm with airway occluded as a function of lung volume. As lung volume increases, the effectiveness of the diaphragm as a pressure generator decreases. Transdiaphragmatic (P_{di}) and airway (P_{ao}) pressures related to lung volume during constant bilateral phrenic pacing

observations suggested that diaphragmatic function was severely impaired in many of these patients, and that it's function was more impaired in the upright posture than in the supine posture. This work plus the observation that several such patients obtained striking relief of dyspnea from the supine and leaning forward postures stimulated more extensive studies of similar patients.

We subsequently studied 17 COPD patients with varying degrees of hyperinflation, measuring esophageal, gastric and transdiaphragmatic pressures, integrated electromyograms of up to 5 respiratory muscles and thoracoabdominal motion via magnetometers. These measurements were made supine, standing (75° head up on a tilt table), sitting erect and sitting leaning forward. We were particularly interested in seeing whether postural relief of dyspnea might be explained by changes in respiratory muscle function. Figure 13 shows re-drawn tracings from one such patient study. Please note three things from this illustration. First, there is a marked increase in the EMG of the inspiratory muscles studied, particularly the accessory rib cage muscles, in the standing and erect sitting positions as compared with the supine and forward leaning positions. Secondly, the gastric pressure, while showing a positive inspiratory change in the supine position shows a negative inspiratory change in the upright positions. Active transdiaphragmatic pressure is thus considerably less when the patient is upright than when he is supine or sitting leaning forward. Thirdly, inspiratory abdominal motion is outward as is normal in the supine and forward leaning positions but is inward or paradoxical in the standing and erect sitting positions. Figure 14 summarizes in chart form the essential information from this study. Note the marked increases in respiratory muscle EMG's, the decline in abdominal pressure and transdiaphragmatic pressures and the reversal of abdominal motion occurring in the standing and erect sitting postures. Also note the improvement obtained upon leaning forward.

We believe the data indicate that the hydrostatic effect of the abdomen lengthened the diaphragm in the supine position, enabling it to function over a more efficient portion of its length-tension diagram. Likewise in the leaning forward posture, forward bending of the spine and formation of a lap caused some compression of the abdominal contents, pushing the diaphragm upward and stretching it, thus improving its length-tension situation. Note in the standing and erect postures that although the pleural pressure change was about the same as in the supine and forward leaning positions, the transdiaphragmatic pressure was considerably less. This tells

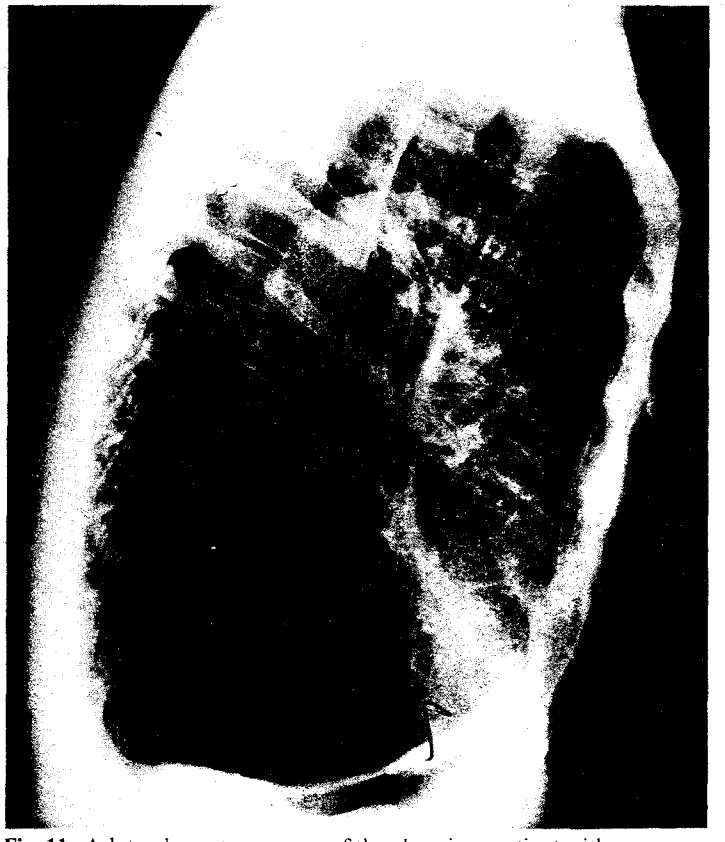

Fig. 11. A lateral roentgenogram of the chest in a patient with severe emphysema showing the low flat diaphragm with its concavity directed uward

us that in these positions, the diaphragm was doing less of the work on the lung and that the accessory and rib cage muscles were doing more of it.

Comparison of seven patients with striking postural relief of dyspnea and paradoxical (inward) inspiratory motion of the abdomen in upright postures with 10 patients with similar FEV_1's but no postural relief or paradoxical abdominal motion showed interesting and significant differences. The seven with postural relief were significantly more hyperinflated than the two without. They also showed greater accessory muscle EMG activity in the upright postures and their patterns of gastric and transdiaphragmatic pressure change with posture were significantly different indicating less effective diaphragmatic function in the erect postures.

In summary, our data suggest that intensification of dyspnea in the erect standing and seated postures and its relief by assuming the supine and/or leaning forward postures have to do with changes in the effectiveness of diaphragmatic function and the necessity for accessory muscles to assume most of the burden of ventilation when the unfavorable postures are assumed.

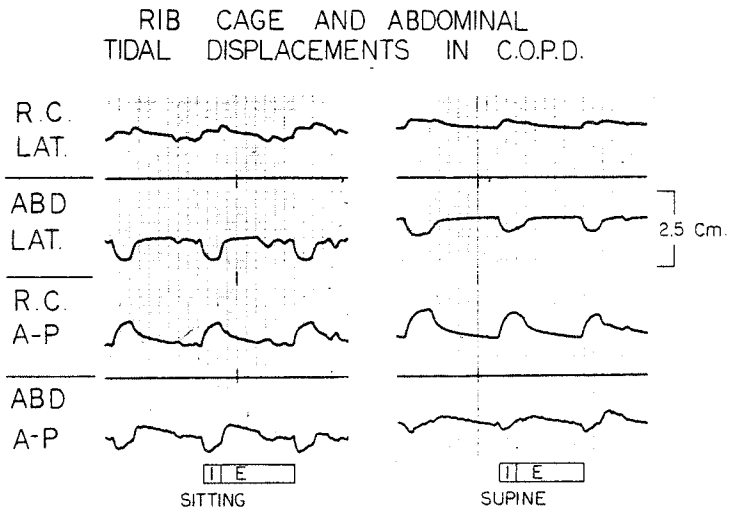

Fig. 12. Thoracoabdominal motion as indicated by magnetometers in a patient with severe chronic obstructive lung disease. The top two tracings represent changes in the lateral diameter of the rib cage and abdomen; the bottom two tracings represent changes in the anteroposterior diameters of the mid rib cage and mid abdomen

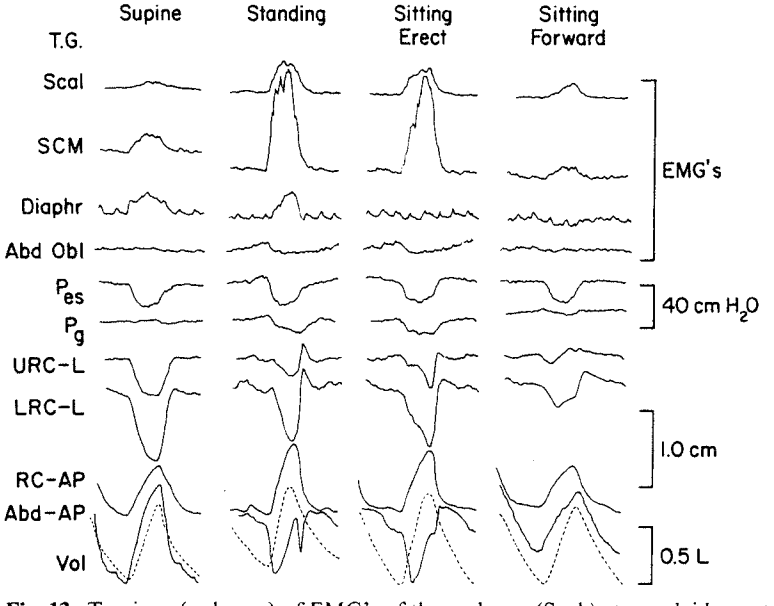

Fig. 13. Tracings (redrawn) of EMG's of the scalence (Scal.) sternocleidomastoid (SCM), diaphragm (Diaphr.) and abdominal oblique (abd. obl.) muscles, esophageal (P_{es}) and gastric (P_g) pressures, thoracoabdominal diameters (magnetometers) and respired volume in a COPD patient who had striking postural relief od dyspnea. URC-L is upper rib cage, lateral; LRC-L is lower rib cage, lateral; RC-AP is rib cage, anteroposterior and Abd-AP is abdomen, anteroposterior. Calibration of all four magnetometer channels is identical as indicated by the 1 cm vertical bracket. The interrupted tracing (bottom) is respired volume with upward deflection indicating inspiration

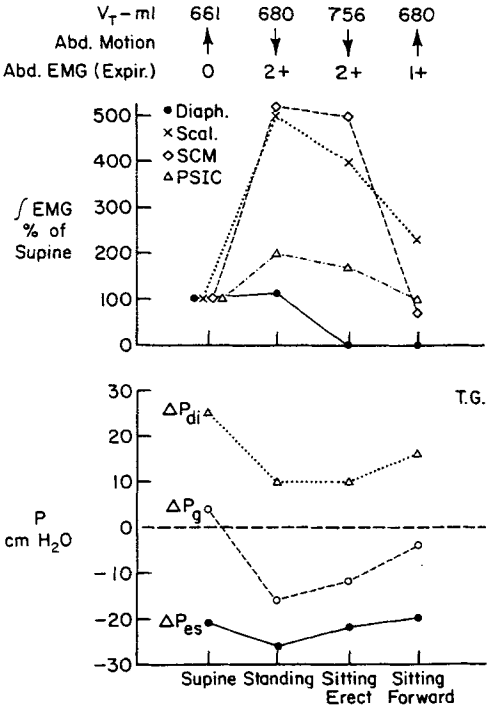

Fig. 14. Data from the same patient as in Fig. 13 given in numerical and graphic form. In reference to abdominal motion, upward arrows indicate outward inspiratory motion, downward arrows, inward inspiratory motion. Abd. EMG refers to EMG activity during expiration over the external oblique abdominal muscle

The question arises concerning the mechanism for postural relief of dyspnea in severe obstructive lung disease. While a general discussion of the mechanisms of dyspnea is beyond the scope of this paper, some discussion of dyspnea in obstructive lung disease is in order. Most would agree that dyspnea and disability in this disease is more related to mechanical abnormalities of the respiratory system than to defects in gas exchange. Indeed it is not unusual to see only mildly abnormal arterial blood gases in patients with severe dyspnea and disability.

Barach [3] believed that dyspnea was related to the excessive and obligatory use of accessory inspiratory muscles in a situation (marked hyperinflation) in which the diaphragm could not function effectively. Campbell and Howell [4] have advanced the theory of length-tension inappropriateness which suggests that mechanoreceptors in overworked muscles bombard the respiratory centers with impulses and touch off the symptom of dyspnea. Finally, the work of Ramsay [29, 30] and of Levine [21, 22, 23] suggest that chemoreceptors in thoracic musculature which respond to some metabolite(s) produced by working (and overworked) muscle may be involved in the dyspneic sensation.

Irrespective of which of these three hypothesis one favors, postural relief of dyspnea is explainable if one considers the data just reviewed. The leaning forward and supine positions appear to improve diaphragmatic function by improving the diaphragm's length-tension status. Thus, the diaphragm generates more pressure for the same or lesser neurogenic input, making its outpout parameters (shortening and force) more appropriate to each other and to its neurogenic input. The improved function of the diaphragm allows the accessory muscles to reduce the amount of

work they do, which decreases the stimulus to respiratory centers arising from mechanoreceptors or chemoreceptors in these muscles. Finally, the hypothesized chemoreceptors in the diaphragm and rib cage inspiratory muscles are stimulated less since the muscles are less overworked, and fewer impulses from this source impinge upon the respiratory centers.

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