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The rib cage and abdominal components of respiratory system compliance in tetraplegic patients

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The rib cage and abdominal components of respiratory system compliance in tetraplegic patients. J.M. Goldman, S.J. Williams, D.M. Denison.
ABSTRACT: The specific compliance of the chest wall and lungs combined was measured in eight patients with stable tetraplegia. Expiration was impeded with a series of spring-loaded resistances, and end-expiratory pressures plotted against changes in chest wall volume at end-expiration. An optical contour mapping system was used to partition changes in chest wall volume into rib cage and abdominal components. These measurements suggest that the compliance of the whole system is reduced by one third in patients with stable tetraplegia, compared with normal subjects. This may be because of abnormal stiffening of the rib cage.
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Immediately after surviving high-spinal injury, patients can breathe with their diaphragm and accessory muscles, but not with their intercostal or abdominal muscles. Excursions of the diaphragm are defeated by paradoxical motion of the flaccid rib cage to an extent determined by the stabilizing action of the scalenes and sterno-mastoids [1]. In subsequent weeks paradoxical motion of the chest wall diminishes [2] and the compliance of the whole system (lungs, rib cage and abdomen combined) is less than in normal subjects [3, 4]. Recently we found that such patients had abdominal walls that were twice as compliant as those of healthy people [5], suggesting that the change in overall compliance is due to stiffening of the rib cage. The object of this study was to use a non-invasive method to measure total respiratory system compliance in tetraplegic patients and to partition it into rib cage and abdominal components.

Patients and methods

We studied eight patients with trauma induced tetraplegia who had no history of lung disease; three had been smokers. Their mean age was 27 yr and six were male. All were judged to have suffered complete transection of the cervical spinal cord and had no detectable motor or sensory function below the levels indicated in table 1. They were investigated at least three months after injury, at a time when they were free from any added respiratory complication.

Patients were examined supine under an optical contour mapping system [6]. A pattern of horizontal stripes was projected onto either side of the subject and the resultant contour lines, formed on the trunk, were photographed from above, with a 35 mm camera. Information about the shape and volume of the chest wall was retrieved by projecting the photograph onto a digital plotting table connected to a Prime-750 computer. This system defines the spatial co-ordinates of approximately 1000 points on the surface of the trunk [7]. It can be employed to separate the volume displacements of the rib cage and abdominal compartments, by using the lower costal margin as a boundary [2]. This margin was visible in each photograph.

Patients breathed through the respiratory apparatus shown in figure 1. The mouthpiece was attached to an unheated fabric-screen pneumotachograph, which led directly to a conventional two-way (inspiratory-expiratory) valve box, arranged so that the expiratory part could be impeded by additional spring-loaded valves of known characteristics. The resistances used were commercially available positive end-expiratory pressure valves (Medicaid) with opening pressures of 0.25, 0.5, 0.75, 1.0 and 1.25 kPa. A tapping at the mouthpiece led to a strain-gauge transducer (Elema-Schonander EMT 35) which provided a record of mouth pressure. The tappings on either side of the fabric screen led to a differential strain-gauge pressure transducer (Elema-Schonander EMT 32) that gave a signal of the respired flow. This equipment was used purely to load expiration, detect the end of expiration and record the mouth pressure and therefore alveolar pressure at the time of no flow. The apparatus had an anatomical dead space of 130 ml.

The mouth pressure transducer was calibrated against a water manometer before and after each study, and was linear to within 0.02 kPa over the range 0–6.0 kPa. The respired flow signal was integrated to obtain the respired volume. This introduced a signal delay of 10 ms. Respired volume

Table 1. - Tetraplegic patients studied

Patient	Sex	Age yr	Level of lesion	Time after injury	Predicted TLC l
1	M	24	C6	4 yr	6.6
2*	F	25	T1	4 mth	5.8
3	M	34	C5,6	7 mth	7.0
4*	F	35	C5,6	6 mth	5.0
5	M	31	C5	6 mth	6.75
6	M	27	C5	4 mth	7.75
7*	M	29	C5	9 mth	5.8
8	M	20	C5	19 mth	7.0

M: male; F: female; *: smoker, TLC: total lung capacity, C: cervical spine segment, T: thoracic spine segment.

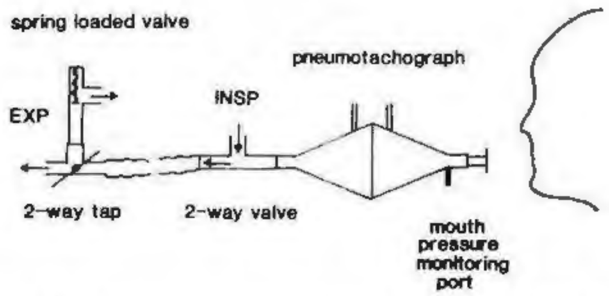

Fig. 1. Diagrammatic representation of the apparatus used to apply an expiratory threshold resistance to tetraplegic patients, and record airway pressure and phase of respiration.

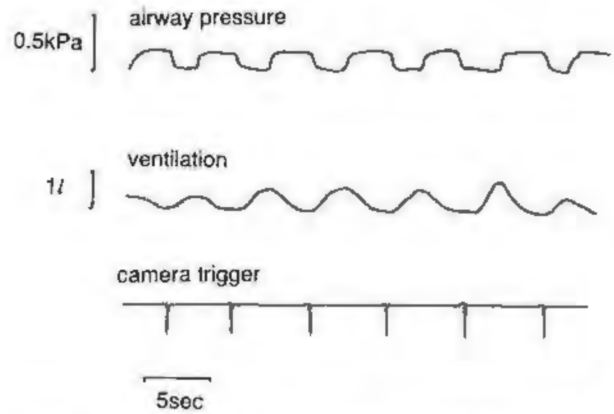

Fig. 2. A typical trace of airway pressure, ventilation, and the camera trigger, recorded from a tetraplegic patient breathing with an expiratory threshold resistance.

and mouth pressure, together with a shutter-opening signal from the camera, were displayed on a multichannel thermal pen recorder (Gould 4400), as shown in figure 2.

Protocol

Patients at rest were supine beneath the optical frame and breathed spontaneously throughout. The camera was triggered manually to obtain photographs (of abdominal and rib cage volume) at the end of unimpeded expiration and then at the end of the last five of ten breaths opposed by resistances that were increased progressively from 0.25 to 1.25 kPa. The photograph which was closest to true end-expiration in each series of five was selected by inspection of the pen recording and used to relate abdominal, rib cage and trunk volumes to the mouth pressure measured at the time. Patients were allowed a few minutes unimpeded breathing between each obstruction. The body volumes were calculated from the photographs as described in [6].

Results

The open circles in figure 3 plot the increases in trunk volume, relative to functional residual capacity (FRC), seen in each patient as end-expiratory pressures increased. Data are normalized to predicted total lung capicity (TLC) [8] to eliminate the effects of differences in body size. The broken lines show regressions constrained to pass through the origin of the graph in each case. The slope of these lines have been taken as a measure of specific respiratory system compliance for each individual. Values for these slopes are listed in table II. The relationship is linear in seven of the eight patients ($r > 0.96$), but not in the eighth ($r = 0.64$ in patient 7). The mean slope for all eight patients is 0.81 $ml \cdot kPa \cdot l^{-1}$ TLC (SD=0.41 $ml \cdot kPa \cdot l^{-1}$ TLC).

The solid circles in figure 3 plot the volume

Table 2. - Respiratory system compliance in tetraplegic patients

Patient	Total Resp. System		Abdominal Compartment		
	Specific compliance	Corr. coeff.	Specific compliance	Corr. coeff.	sCabd/sCrs
	$ml \cdot kPa \cdot l^{-1}$ TLC	r	$ml \cdot kPa \cdot l^{-1}$TLC	r	%
1	0.912	0.98	0.956	0.99	105
2	1.102	0.99	1.034	0.99	94
3	1.485	0.99	0.027	0.97	69
4	0.570	0.98	0.306	0.86	54
5	0.787	0.97	0.471	0.89	60
6	0.229	0.93	0.186	0.95	81
7	0.359	0.64	0.402	0.77	110
8	1.102	0.99	0.340	0.95	31

Specific compliance of the total respiratory system and its abdominal compartment in tetraplegic patients, with the correlation coefficients of each plot. sCabd/sCrs: specific compliance abdominal/specific compliance respiratory system in %.

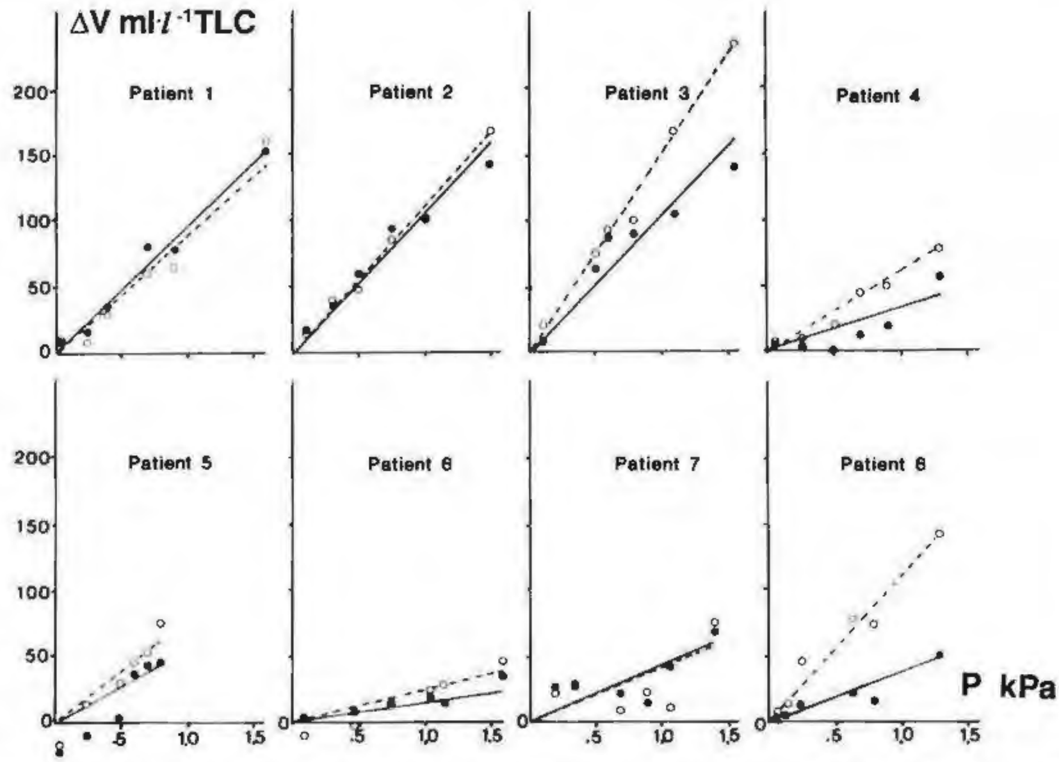

Fig. 3. Specific compliance plots of the total respiratory system and its abdominal compartments in tetraplegic patients. ΔV: change in volume above resting FRC expressed in $ml \cdot l$ predicted TLC; P: airway pressure in kPa. Black data points and solid lines represent data pertaining to the abdominal compartment. White data points and broken lines represent data pertaining to the total respiratory system.

displacements of the abdominal wall, relative to FRC, seen in each patient as end-expiratory pressures increased. Data are again normalized to predicted TLC. The solid lines show regressions constrained to pass through the origin of the graph in each case. The slope of this line has been taken as a measure of the specific compliance of the abdominal pathway. It accounts for all, or almost all, of the specific compliance of the whole system in patients 1, 2, 3, 5, 6, and 7, and half or slightly less than half of the whole system compliance in patients 4 and 8 (see table 2). The mean slope for the abdominal pathway represents $75.5 \pm 27.2\%$ of system compliance, in the group as a whole.

Discussion

At the end of an expiration there is no movement of air into or out of the lungs even though the glottis is open. Since there is no flow, alveolar pressure and mouth pressure are equal. The system is stationary and the various forces within it must be at equilibrium. When positive end-expiratory pressure is added to the system and quiet breathing continues, we have supposed that the slope of the pressure-volume curve of the trunk measures the compliance of the relaxed respiratory system at FRC and above. We have assumed that the respiratory muscles of tetraplegic patients are relaxed at end-expiration. It is possible that there is reflex activity in the abdominal or intercostal muscles, but, by definition, these patients have no control over such activity and we feel that measurement of the 'effective' compliance of the respiratory system is valid.

Our method is analogous to the weighted spirometer technique of HEAF and PRIME [9]. Instead of weights, expiratory threshold resistances were used to load expiration. Instead of a spirometer to measure respired volume, the optical contour mapping system was used to measure changes in chest wall volume. This system is accurate in partitioning chest wall volume into its rib cage and abdominal components, with 95% confidence limits of 1% of the measured volume of the abdominal component [10]. Both the weighted spirometer technique and the method used in this study measure total respiratory compliance. Since airway pressure is plotted against change in chest wall volume, it is the compliance of the whole system, including the lungs, which is represented by the gradient of the plot. To normalize the data for patients with different body size, results have been divided by predicted TLC, and expressed as specific compliance.

VELLODY *et al.* [11] refined the weighted spirometer method by using magnetometers to measure rib cage and abdominal pathway compliance separately in normal subjects. ESTENNE *et al.* [4] applied a similar method to patients with respiratory muscle weakness, including ten patients with complete neurological lesions of the cervical spinal cord (eight due to trauma and two due to transverse myelitis). They measured lung compliance with an oesophageal balloon to derive true chest wall compliance, but could not separate it into abdominal and rib cage components with any certainty. More recently, the same group [3] measured chest wall compliance in twenty seated tetraplegic patients using a weighted spirometer technique and, by using pairs of linear magnetometers, derived rib cage and diaphragm-abdomen compliance. We have applied the optical contour mapping system in this situation and believe it has advantages, as it measures change in chest wall volume rather than extrapolating from change in diameter. It will therefore take into account any asymmetric or paradoxical movement.

Expiratory threshold resistances were used to load breathing. CAMPBELL *et al.* [12] exposed conscious and anaesthetized normal subjects to such resistances, and found that FRC increased with addition of the load, and decreased to normal after it was removed. In conscious subjects, this pattern was seen even if the load was present for only 4–10 breaths. An increase in end-expiratory volume occurred from the first loaded breath and was complete after three or more breaths. In the present study, loads were applied for ten breaths and end-expiratory volume measured after at least five breaths. D'ANGELO and AGOSTONI [13] noted that this response to expiratory threshold resistances was abolished by vagotomy in dogs, and that it was not altered by T1 cordotomy. This evidence suggests that response to expiratory threshold resistance is mediated via the vagus and should therefore be intact in patients with cervical cord injury. AXEN [14] has made detailed studies of loading inspiration in tetraplegic patients and found their response similar to normal subjects.

In the present study FRC rose linearly with the addition of expiratory threshold resistance in seven out of eight patients. VELLODY *et al.* [11] found a linear increase in end-expiratory volume as airway pressure increased in normal subjects whether they were relaxed ($0.0077\ l \cdot kPa^{-1}$) or anaesthetized and paralysed ($0.0078\ l \cdot kPa^{-1}$). Using the data from VELLODY *et al.* [11], specific compliance of the respiratory system has been calculated for each of the paralysed and anaesthetized normal subjects that they studied. This data is displayed in table 3, and may be compared to the data for tetraplegic patients in table 1. The mean specific compliance of the respiratory system for paralysed normal subjects was 1.237 $ml \cdot kPa^{-1} \cdot l$ TLC (SD 0.336 $ml \cdot kPa^{-1} \cdot l$ TLC), whilst for the tetraplegic patients of the present study, it was 0.813 $ml \cdot kPa^{-1} \cdot l$ TLC (SD 0.41 $ml \cdot kPa^{-1} \cdot l$ TLC), which is 65.7% of normal. The data for normal subjects and tetraplegic patients were compared using an unpaired Student's t-test. There was a significant difference between the two groups ($p < 0.05$).

A low effective respiratory system compliance amongst supine tetraplegic patients supports the findings of ESTENNE *et al.* [4] in a similar seated group. Their published data of lung and chest wall compliance were used to derive respiratory system compli-

Table 3. - Respiratory system compliance in normal subjects

Subject	Height cm	TLC l	sCrs ml·kPa^{-1}·l^{-1} TLC	% partitioned to abdominal compartment
1	175	6.35	1.024	46.2
2	183	6.97	1.019	37.2
3	162	5.34	0.749	60.6
4	188	7.36	1.421	58.0
5	170	5.96	1.628	46.4
6	183	6.97	1.365	52.6
7	170	5.96	1.040	53.2
8	168	5.80	1.310	42.1
9	173	6.19	1.309	46.9
10	175	6.35	1.874	47.1
11	178	6.58	0.866	62.2

Specific compliance of the total respiratory system, and the percentage partitioned to the abdominal compartment in normal paralysed anaesthetized subjects from the data of VELLODY *et al.* [11].

ance for their ten patients with tetraplegia. The mean compliance of the respiratory system was 0.0082 l·kPa^{-1}, while in normal subjects it was 0.0135 l·kPa^{-1}. They suggested that this decrease was due predominantly to a decrease in rib cage compliance, and subsequently confirmed this by direct measurement using magnetometers [3]. The tetraplegic patients in the present study partitioned 24.5% of the specific compliance of the respiratory system to the rib cage pathway, whilst the normal subjects in the study of VELLODY *et al.* [11] partitioned a mean of 50% to the rib cage. We did not measure lung compliance in our patients, as we were aiming to develop a non-invasive technique for clinical application. A decrease in lung compliance in tetraplegia of up to 30% is well described [4], but this will not have a preferential effect on rib cage or abdominal pathway compliance. The ratio between absolute rib cage and abdominal compliance will be the same as that between the rib cage and abdominal pathways of total respiratory system compliance. This ratio in our study was 25% to 75%, *i.e.* 3 to 1. In normal subjects it is 1 to 1. Since we know that abdominal wall compliance is doubled in tetraplegic patients [5] and we have found respiratory system compliance to be reduced, we would suggest that rib cage compliance is less than normal.

Our findings agree those of ESTENNE and DE TROYER [3] who measured chest wall compliance in twenty seated tetraplegic patients, and found it reduced to 72% of normal. This was due to a decrease in rib cage compliance to 55% of normal, whilst abdominal compliance was increased to 170% of normal. We have observed that, in our patients, respiratory system compliance is made up almost entirely by the abdominal pathway. In normal supine subjects, the rib cage is stiffer and the abdomen more compliant than it is in the erect posture [15, 16]. This is compatible with our findings, and additionally we know that the abdominal wall compliance is twice the normal in tetraplegic patients [5] whilst the rib cage is known to be less compliant than normal [3]. In this situation, if the respiratory system is passively inflated, the increase in volume will be partitioned to its most compliant pathway until the compliances of the two pathways equilibrate.

Residual respiratory muscle activity might also effect the relative compliances of the rib cage and abdomen. DE TROYER *et al.* [17] have shown that seated tetraplegic patients may use the clavicular portion of the pectoralis major during active expiration. This muscle, if activated by end-expiratory pressure, could decrease rib cage compliance. However, since our patients were studied supine during relaxed breathing, we think this unlikely. Another possible explanation for our findings would be the systematic overestimation of the increment in chest wall volume partitioned to the abdominal compartment. This seems unlikely, given the 95% confidence limits we have quoted for our method. However, it must be remembered that each point plotted represents a value derived from photographs taken at FRC and at a given end-expiratory pressure. A combination of two sets of errors might explain the results in the two patients who partitioned more than 100% of respiratory system compliance to the abdominal pathway, but will not alter the general trend of our results.

Conclusion

In normal subjects who have been anaesthetized and paralysed, the volume of the rib cage and abdomen increases in parallel when expiration is loaded [16]. In six out of the eight tetraplegic patients studied, the abdominal compartment contributed almost all the increase in chest wall volume. Since the intercostal and abdominal muscles are paralysed in both these groups, the decrease in respiratory system compliance in tetraplegic patients may be due to the rib cage itself becoming stiffer (for example, due to boney ankylosis of joints), or to spasticity of the intercostals. We conclude that the specific compliance of the total respiratory system of tetraplegic patients is less than that of normal subjects, probably because of a decrease in rib cage compliance. This stiffness will limit paradoxical motion of the rib cage and may be an advantage.

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