ORIGINAL ARTICLE

Observational study of the effect of obesity on lung volumes

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ABSTRACT
Background Severe obesity causes respiratory morbidity and mortality. The impact of obesity on the mechanics of breathing is not fully understood.
Patients and methods We undertook a comprehensive observational study of lung volumes and elasticity in nine obese and nine normal weight subjects, seated and supine, during spontaneous breathing. Seated and supine total lung capacity (TLC) and subdivisions were measured by multibreath helium dilution method. Using balloon catheters, oesophageal (Poes) and gastric (Pgas) pressures were recorded. Transpulmonary pressure (P_L) was calculated as mouth pressure (Pmouth)-Poes, and complete expiratory P_L volume curves were measured.
Results The obese group had a body mass index (BMI) of 46.8 (17.2) kg/m^2, and the normal group had a BMI of 23.2 (1.6) kg/m^2 (p=0.001). Obese and normals were matched for age (p=0.233), gender (p=0.637) and height (p=0.094). The obese were more restricted than the normals (TLC 88.6 (16.9) vs 104.4 (12.3) % predicted, p=0.033; FEV_1/FVC 79.6 (7.3) vs 82.5 (4.2) %, p=0.325), had dramatically reduced expiratory reserve volume (ERV 0.4 (0.4) vs 1.7 (0.6) L, p<0.001) and end-tidal functional residual capacity (FRC) was smaller (37.5 (6.9) vs 46.9 (4.6) %TLC, p=0.004) when seated, but was similar when supine (39.4 (7.7) vs 41.5 (4.3) %TLC, p=0.477). Gastric pressures at FRC were significantly elevated in the obese (seated 19.1 (4.7) vs 12.1 (6.2) cm H_2O, p=0.015; supine 14.3 (5.7) vs 7.1 (2.6) cm H_2O, p=0.003), as were end-expiratory oesophageal pressures at FRC (seated 5.2 (6.9) vs −2.0 (3.5) cm H_2O, p=0.013; supine 14.0 (8.0) vs 5.4 (3.1) cm H_2O, p=0.008). BMI correlated with end-expiratory gastric (seated R^2=0.43, supine R^2=0.66, p<0.01) and oesophageal pressures (seated R^2=0.51, supine R^2=0.62, p<0.01).
Conclusions Obese subjects have markedly increased gastric and oesophageal pressures, both when upright and supine, causing dramatically reduced FRC and ERV, which increases work of breathing.

Key messages

What is the key question?
► Obesity is associated with changes of lung volumes, but the physiological origin of this is unknown.

What is the bottom line?
► The main abnormalities in obesity are the transmission of the high pressures in the intra-abdominal compartment to the thorax that dramatically reduce functional residual capacity and expiratory reserve volume and oblige patients to breathe on a flatter, less efficient, part of their pressure–volume curve, increasing the work of breathing.

Why read on?
► This comprehensive study, for the first time, measures the entire expiratory pressure–volume curve in spontaneously breathing and non-sedated obese subjects, explaining the increased work of breathing and analysing the relationship between intra-abdominal pressures and altered lung volumes.

INTRODUCTION
The huge increase in obesity in recent decades requires urgent public health strategies for adults[1–3] and children[4] and a better understanding of the abnormalities of breathing by those caring for obese patients. From a respiratory perspective, it is accepted that compared with subjects with normal weight, obese subjects can have a reduced total lung capacity (TLC)[5,6] and breathe at a lower functional residual capacity (FRC).[7–10] Obesity increases work of breathing, neural respiratory drive,[11,12] breathlessness,[13] causes sleep-disordered breathing and eventually hypercapnic respiratory failure.[7,14,15] However, the details of the abnormal underlying pulmonary mechanics remain to be elucidated.

Changes in lung volumes with posture are important.[16–19] In normal subjects, FRC falls when changing from the seated to the supine posture. In contrast, obese subjects,[8] who breathe closer to residual volume (RV) when seated, may reach closing volume of the airways, and FRC may not decrease further with recumbency.[20,21] Obese subjects can develop intrinsic positive end-expiratory pressure (PEEPi),[22,23] and some have a higher threshold inflation airway pressure.[23] A study by Pelosi et al[24] in sedated and paralysed morbidly obese subjects suggested that high intra-abdominal pressures may have an important effect on mechanical properties of the respiratory system, but the methodology used did not allow their findings on operating lung volumes to be extrapolated to spontaneously breathing subjects.

Therefore, the aim of the present study was to undertake a comprehensive study to determine the

factors contributing to impaired lung mechanics in obese but otherwise healthy people in both seated and supine postures.

PATIENTS AND METHODS

The study was approved by King's College Hospital local research ethics committee. We approached obese but otherwise healthy patients, usually attending for consideration of bariatric surgery, and normal subjects at King's College Hospital to participate. Each participant gave written informed consent. None of the participants was an active smoker, three of the obese and two of the normal subjects were ex-smokers, each one of them with a smoking history of less than 10 pack-years.

The methods used in this study have been established in clinical practice;[25–28] for a more detailed report on measurements of anthropometric data, lung function, dynamic compliance, pressures and electromyogram (EMG), please refer to the online supplement.

The ratio of oesophageal to mouth pressure measured during efforts against an occlusion (Poes:Pmouth) was used to verify correct placement of the oesophageal balloon catheter. It was 1.05 (0.06) seated in normal vs 1.01 (0.08) in obese subjects (p=0.299) and 0.98 (0.05) in the normal vs 0.93 (0.04) in the obese when supine (p=0.039).

Breathing manoeuvres
Resting breathing and recording of pressure volume curves

Resting breathing was recorded for 2 min while relaxed, seated in an arm chair and for 2 min lying supine on a bed, the head resting on a pillow, wearing a noseclip, breathing through a flanged mouthpiece connected to a pneumotachograph. The

subjects then performed three TLC manoeuvres through a spirometer (Morgan, Massachusetts, USA), followed by brief and stepwise occlusions and openings of the mouthpiece at different lung volumes, to obtain pressure–volume (PV) curves over the complete expiratory vital capacity (figure 1). The measurements were repeated 3–5 times when seated and 3–5 times when supine. In addition, as the spirometer provided a closed system, we were able, as the subjects moved from the seated to the supine posture, to determine changes in FRC and TLC. For this purpose, subjects performed an inspiratory capacity (IC) manoeuvre seated and, allowing several tidal breaths to adjust for the new posture, another IC manoeuvre when reclined in a chair, tilted backwards with the body horizontal. They were then made to sit upright again to perform a third IC manoeuvre. Subjects stayed connected to the mouthpiece while undergoing this manoeuvre, and this enabled the measurement of differences in IC and TLC (figure 2). The manoeuvre was repeated 2–3 times.

Statistical analysis

We analysed data from all recorded PV curves. Mean and SD are reported for normally distributed data. Correlations are reported between variables using the R^2-value. Group differences were compared using an unpaired t test, and changes in parameters when changing posture from the seated to the supine were analysed with paired t tests. Fisher's exact test was used to analyse categorical data (gender). Differences were considered to be of significance with a p<0.05.[29] For a more detailed report on the sample size calculation, please refer to the online supplement.
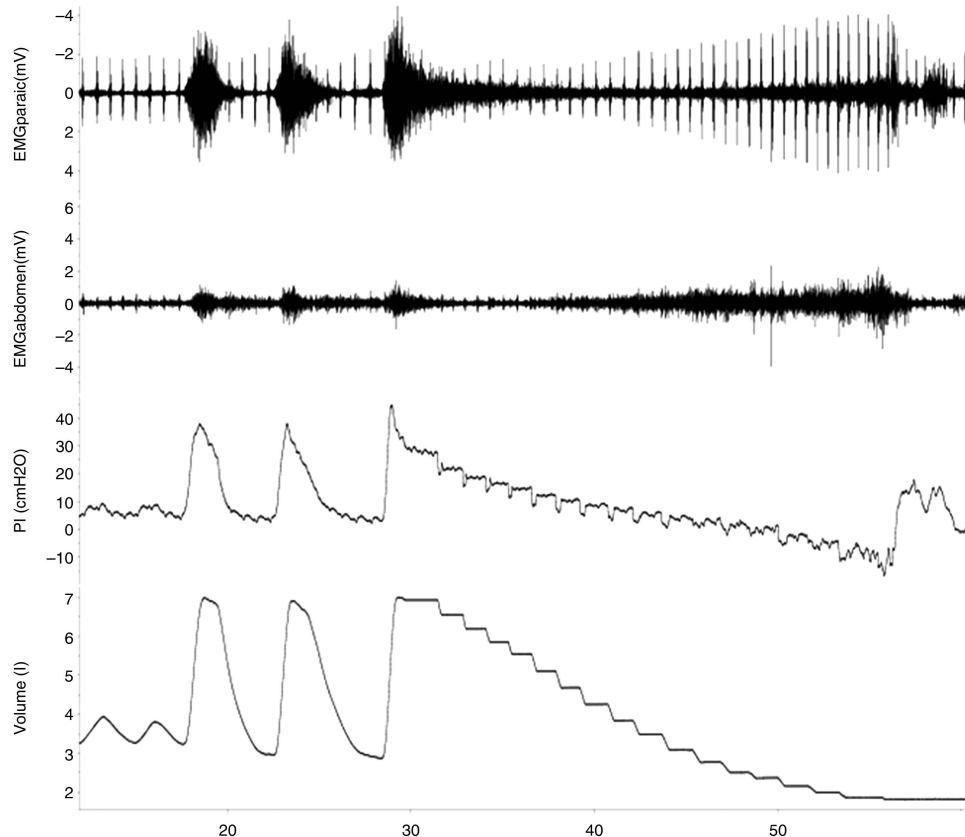

Figure 1 Breathing manoeuvre performed to generate the pressure–volume curves. EMG parasternal intercostals activity (top trace) and EMG abdominal muscles (second trace), muscle activity can be clearly identified in inspiration between the ECG artefacts. Inspiratory muscle activity declines until functional residual capacity (FRC) is reached and expiratory muscle activity then increases at lung volumes below FRC. X-axis indicates time in seconds.

Figure 2 Simplified schematic illustration of lung volumes seated and supine in normal and obese subjects, expressed as litres (upper panel) and per cent predicted TLC (lower panel). Parameters are derived from tables 2 and 3. TLC, total lung capacity; IRV, inspiratory reserve volume; V_t, tidal volume; ERV, expiratory reserve volume; RV, residual volume.
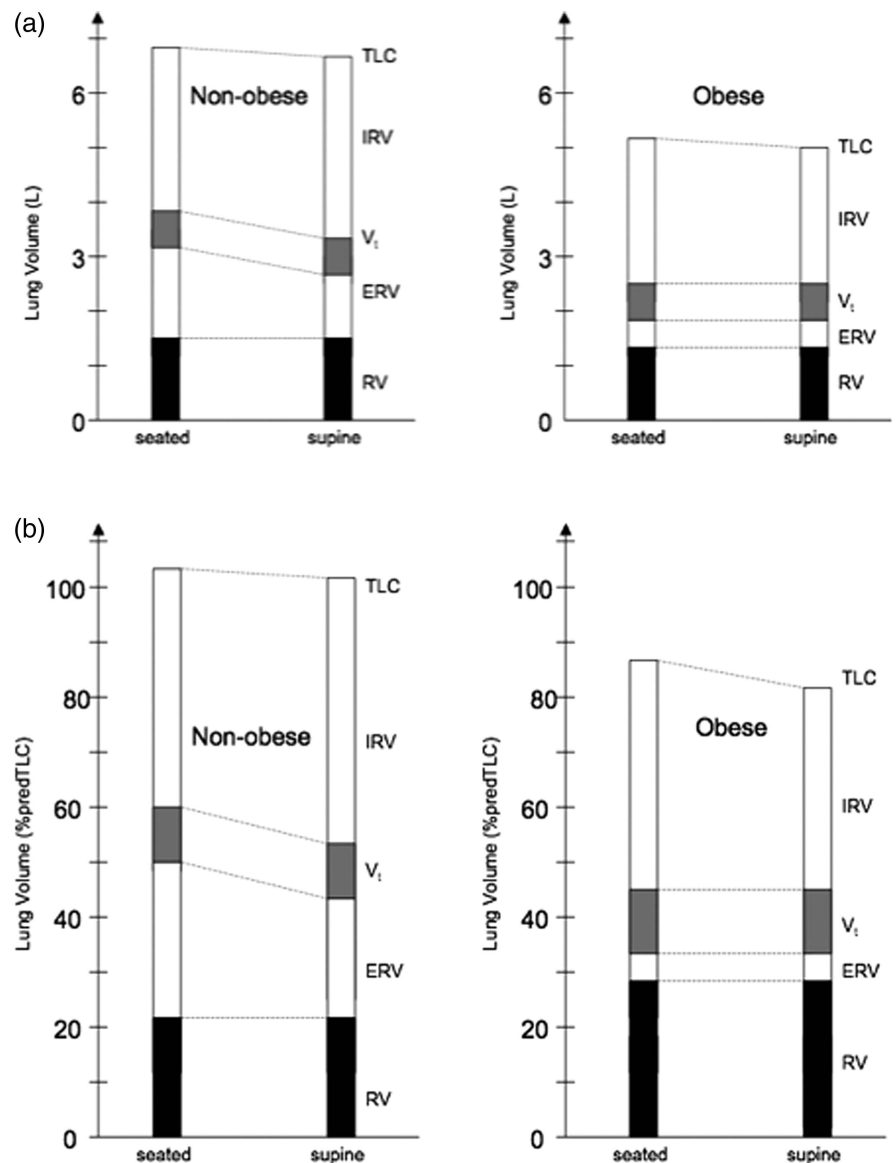
RESULTS

Subjects

We studied nine obese subjects (mean (SD) body mass index (BMI) 46.8 (17.2) kg/m^2) and nine normal weight controls (mean (SD) BMI 23.2 (1.6) kg/m^2). Three of the obese subjects and two of the control subjects were ex-smokers (<10 pack-years), but all had a normal FEV_1/FVC ratio. The two groups were matched for gender, age and were similar in height. The obese group were more breathless than normals. Waist circumference correlated with the amount of fat tissue deposited in the abdominal wall (abdominal skin fold double layer vs waist circumference; R^2=0.69, p<0.001; table 1).

Spirometry and lung volumes

FEV_1 and FVC (L) were reduced in the obese subjects. Obese subjects had a smaller TLC, expressed as per cent predicted, and a smaller vital capacity. IC (defined as TLC minus FRC) was not different between the groups when seated. Seated FRC was reduced in the obese, both measured in litres and expressed as FRC/TLC. Although FRC was larger in the supine posture when expressed as volume (in litres) in normals, it was similar between the groups when expressed as per cent of TLC. RV in absolute volume (litres) was similar in both groups, but RV/TLC

in the obese subjects was higher. Expiratory reserve volume (ERV) was significantly reduced in the obese (table 2; figure 2). Waist circumference correlated negatively with FRC (R^2=0.47, p<0.01) and with TLC, expressed as per cent predicted (R^2=0.41, p<0.01; figures 3 and 4).

Reduction in TLC when supine was small and similar in normal and obese groups (−0.24 (0.08) L in normal vs −0.25 (0.08) L in obese subjects, p=0.70). When supine, IC decreased only in the obese subjects and FRC remained constant in both postures in obese subjects. In normal subjects, IC increased when changing to the supine posture, despite a decrease in TLC, with a fall of approximately 500 mL in FRC with change in posture (table 2, figure 2). In contrast, IC did not change in the obese group and five obese subjects had no measurable ERV when supine.

Dynamic and static lung compliance

Tidal volume (V_t) was similar between the groups and did not change significantly with posture. Seated dynamic lung compliance, when expressed as %predicted TLC in order to correct for differing height and gender, was not different between groups. With change in posture to the supine position, dynamic compliance decreased in both groups (table 3; figures 3 and 4).

Table 1 Anthropometry and spirometry

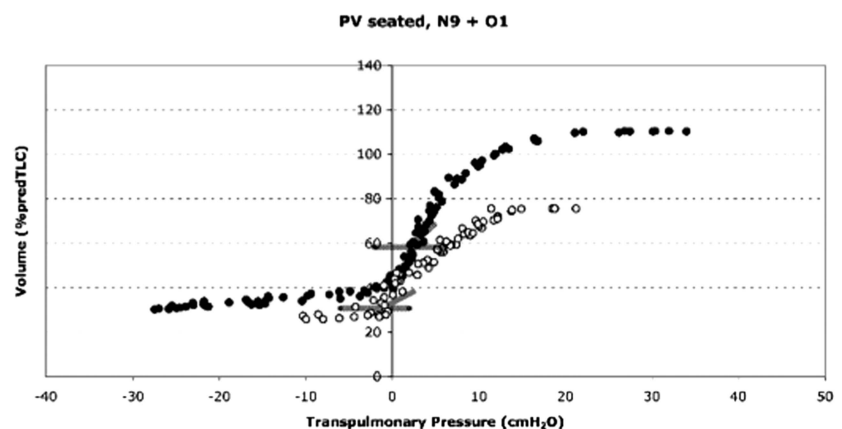| Parameter	Normal group	Obese group	p Value
Age (year)	38 (11)	45 (13)	n.s.
Gender (m:f)	5:4	4:5	n.s.
Height (m)	1.75 (0.10)	1.65 (0.12)	0.094
Weight (kg)	71.4 (12.5)	124.9 (36.0)	0.001
BMI (kg/m^2)	23.2 (1.6)	46.8 (17.2)	0.001
Neck circumference (cm)	35.1 (2.4)	43.4 (3.2)	<0.001
Waist (cm)	81.3 (9.3)	122.8 (18.9)	<0.001
Hip (cm)	95.9 (5.6)	127.8 (20.6)	<0.001
Waist:hip ratio	0.85 (0.07)	0.96 (0.09)	0.006
MRC Dyspnoea Score (points)	1.0 (0.0)	2.4 (1.2)	0.003
FEV$_1$ (L)	4.4 (1.0)	3.0 (1.5)	0.033
FEV$_1$ (%predicted)	119.6 (17.8)	97.4 (24.7)	0.044
FVC (L)	5.3 (1.3)	3.7 (1.8)	0.043
FVC (%predicted)	125.2 (17.3)	96.8 (19.7)	0.005
FEV$_1$/FVC (%)	82.5 (4.2)	79.6 (7.3)	0.325
Sagittal abdominal diameter/SAD (cm)	21.1 (2.0)	33.3 (7.7)	<0.001
Delta SAD$_{inspiration}$ (cm)	2.7 (1.0)	2.6 (0.3)	0.649
Double skinfold abdomen (mm)	14.4 (5.3)	47.2 (19.6)	<0.001

Demographics and body features of the obese and normal groups in mean (SD); the normal group included one subject who was slightly overweight (BMI 25.4 kg/m^2). Spirometry was used as an entry criterion to confirm that obese subjects did not have significant obstructive airway disease.

A calculated mid-range slope of the static expiratory PV curves revealed no significant difference between the groups within the range of 50–60% predicted TLC, but there was reduced compliance between 60 and 70% of predicted TLC in the obese subjects, seated and supine (table 4; for individual PV curves, please review the online supplement).

End-expiratory pressures at FRC during tidal breathing

At FRC, end-expiratory oesophageal pressures were higher in the obese group when seated and supine. Both groups revealed a similar increase (mean change of 7.4 vs 8.8 cm H$_2$O) in the mean oesophageal pressure when changing to the supine posture. End-expiratory gastric pressures were higher in the obese group, seated and supine. However, intra-abdominal pressures fell when changing from the seated posture to the supine in both groups by around 5 cm H$_2$O. End-expiratory trans-diaphragmatic pressure was not different between the two groups, sitting and supine, and was consistent with pressure

equilibration between the abdominal and thoracic compartment in supine posture. Transpulmonary pressures were significantly lower at end-expiration in obese subjects, but fell with recumbency by a similar amount in both groups (table 3).

Pressures during maximal inspiratory effort

Pressure changes associated with full lung inflation (IC manoeuvre) revealed no significant differences between the two groups in intrathoracic (Poes), intra-abdominal (Pgas) or trans-diaphragmatic (Pdi) pressures. However, the transpulmonary pressure gradient was reduced in the obese group at TLC when seated and supine (table 4).

Respiratory muscle tests

Inspiratory muscle strength, as assessed by a PImax manoeuvre, was reduced in both postures in the obese subjects compared with normals (table 4).[30]

Correlations

There was a moderate positive correlation between end-expiratory gastric pressure and waist circumference ($R^2=0.52$ seated, $R^2=0.60$ supine, p<0.01). Similarly, the BMI was positively correlated to end-expiratory gastric pressure, seated ($R^2=0.43$, p<0.01) and supine ($R^2=0.66$, p<0.01). End-expiratory gastric pressure was negatively correlated with FRC ($R^2=0.59$ seated, $R^2=0.67$ supine, p<0.01) and ERV ($R^2=0.47$ seated, $R^2=0.28$ supine, p<0.01; both in percent of TLC), and therefore the more obese patients had higher gastric pressures and lower FRC and ERV.

End-expiratory oesophageal pressures were related to end-expiratory gastric pressures ($R^2=0.48$ seated; $R^2=0.68$ supine, p<0.01) and, therefore, also correlated to waist circumference ($R^2=0.48$ seated; $R^2=0.61$ supine, p<0.01) and BMI ($R^2=0.51$ seated; $R^2=0.62$ supine, p<0.01).

DISCUSSION

The main findings of the current study are that obese people, particularly when supine, have raised gastric and oesophageal pressures and associated dramatic reductions of FRC and ERV. The high oesophageal pressure imposes a threshold load on inspiration. The obese individual has the option of breathing at low lung volumes, with limited tidal volume, or increasing V_t by adopting a breathing position on a higher part of the PV curve. The reduced compliance when breathing at lower volumes, as well as the inspiratory threshold load, increase the work of breathing, reflected in elevated levels of neural respiratory drive.[12]

Figure 3 Pressure–volume (PV) curves seated of a normal (N9, male, 66 years, 1.72 m, body mass index (BMI) 23.3 kg/m^2; filled circles) and matched obese (O1, male, 60 years, 1.73 m, BMI 34.4 kg/m^2; open circles) subject. Functional residual capacity (FRC) levels and dynamic compliance are indicated by bold grey bars. The PV curve in the obese is restricted in lung volume and diminished in slope, the FRC is low. Despite the differences in the slope of the static PV curves, the dynamic compliance, illustrated by the diagonal grey bars, is not substantially different between the obese and normal subject.

PV seated, N9 + O1

Figure 4 Pressure–volume curves supine of a normal (N9, filled circles) and matched obese (O1, open circles) subject. Compared with the seated posture, the slope of the curves is diminished, in the obese functional residual capacity approximates residual volume. Dynamic compliance is lower than when seated and more different between obese and normal subject.

PV supine, N9 + O1
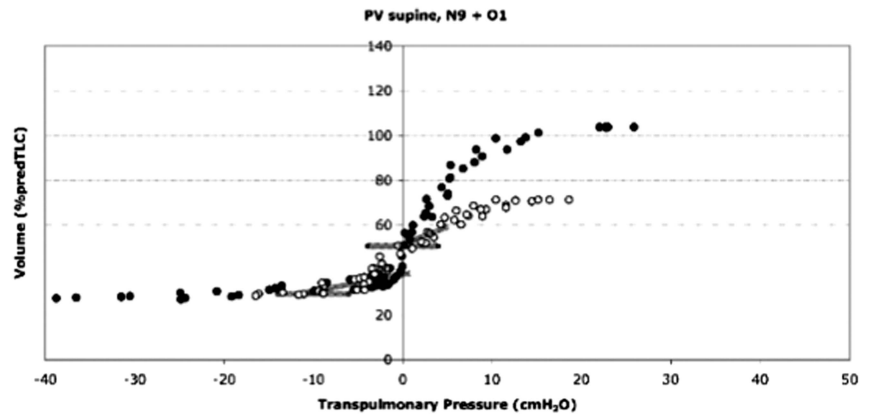
Increased intra-abdominal pressures cause a threshold load on the diaphragm at end-expiration that needs to be overcome prior to any diaphragmatic movement. This leads to higher than normal intrathoracic pressures in obese subjects, particular at end-expiration when transdiaphragmatic pressures indicate a relaxed diaphragm, and it increases further with supine posture. High oesophageal pressures are associated with low FRC and reduced ERV in obesity as they diminish transpulmonary pressures during tidal breathing.

Postural changes in intra-abdominal and intrathoracic pressures become more important in obesity due to reduced ERV and the higher threshold load on the diaphragm. Work of breathing in obesity, which is already high when seated, further increases with recumbency, caused by a disadvantageous impact of gravity. There is equilibration of the high intra-abdominal with intrathoracic pressures because the diaphragm is relatively inactive (table 3).

Significance of the findings

Previously, our group studied neural respiratory drive in obesity and found it to be raised.[12] In that study, we also measured oesophageal and gastric pressures, seated and supine, confirming increased levels of gastric and oesophageal pressures in wakeful

breathing subjects, but the study did not measure lung volumes or transpulmonary pressures.

Data on oesophageal pressures and spirometry in wakeful spontaneously breathing overweight and obese subjects have been published by Owens et al.[31] Although their subjects were less obese (BMI 33.3 (5.7) kg/m^2), they concluded that oesophageal pressure can be reliably measured in the seated and supine posture. However, they did not measure PV curves, abdominal pressures and lung compartments. In this context, it is of interest that Washko et al[19] also assessed the change in transpulmonary pressure in healthy normal subjects that was associated with change in posture from the seated to the supine. They found that P_L decreases by 7.0 cm H_2O, in agreement with our finding that P_L decreases by 7.4 cm H_2O with change in posture in the normal group and by 8.8 cm H_2O in the obese subjects.

Behazin et al[23] studied obese and normal subjects supine, anaesthetised and paralysed perioperatively. They measured Poes at relaxation volume (Poes, rel) and found it to be above atmospheric pressure, 12.5 (3.9) cm H_2O in the obese and 6.9 (3.1) in the normal (p<0.0001) groups, comparable pressure levels to our findings in wakeful subjects breathing at FRC, supine (table 4). Similarly, the gastric pressures of the obese group in their study were within the range of our observations

Table 2 Total lung capacity and subdivisions, seated and supine

Parameter	Normal group, seated	Obese group, seated	p Value	Normal group, supine	Obese group, supine	p Value
TLC (L)	6.8 (1.7)	5.1 (1.9)	0.065	6.5 (1.7)	4.8 (1.9)	0.058
TLC (%pred)	104.4 (12.3)	88.6 (16.9)	0.033	N/A	N/A	N/A
VC (L)	5.3 (1.3)	3.6 (1.8)	0.035	5.2 (1.2)	3.4 (1.8)	0.030
FRC (L)	3.2 (0.9)	1.8 (0.5)	0.002	2.7 (0.7)	1.8 (0.4)	0.004
FRC/TLC (%)	46.9 (4.6)	37.5 (6.9)	0.004	41.5 (4.3)	39.4 (7.7)	0.477
ERV (L)	1.7 (0.6)	0.4 (0.4)	<0.001	1.1 (0.3)	0.3 (0.4)	<0.001
ERV/TLC (%)	25.8 (6.3)	6.1 (6.4)	<0.001	17.5 (6.4)	4.2 (6.4)	<0.001
RV (L)	1.5 (0.6)	1.5 (0.3)	0.979	1.4 (0.6)	1.4 (0.3)	0.872
RV/TLC (%)	21.2 (4.9)	31.4 (10.1)	0.015	20.4 (5.1)	32.2 (11.1)	0.010
IC (L)	3.6 (0.9)	3.2 (1.4)	0.564	4.1 (1.2)	3.3 (1.5)	0.227

Change of volumes with recumbency	Normal group	Obese group	p Value
Δ TLC (L)	−0.24 (0.08)	−0.25 (0.08)	0.695
Δ IC (L)	0.36 (0.59)	−0.19 (0.15)	<0.016
Δ FRC (L)	−0.51 (0.42)	−0.04 (0.13)	0.05

Lung volumes in obese and normal subjects, seated and supine. Δ indicates the change of volume with recumbency (+, increased volume in supine posture; −, loss of volume in supine posture).
ERV, expiratory reserve volume; FRC, functional residual capacity; IC, inspiratory capacity; RV, residual volume; TLC, total lung capacity.

Table 3 Tidal breathing and dynamic compliance

Parameter	Normal group, seated	Obese group, seated	p Value	Normal group, supine	Obese group, supine	p Value
V_t (L)	0.64 (0.14)	0.63 (0.10)	0.584	0.61 (0.13)	0.67 (0.12)	0.317
V_t (%predTLC)	9.3 (1.4)	11.5 (2.1)	0.017	9.6 (1.8)	12.2 (2.8)	0.031
Cdyn (L/cm H_2O)	0.194 (0.070)	0.142 (0.049)	0.087	0.135 (0.037)*	0.105 (0.024)*	0.057
Cdyn (%predTLC/cm H_2O)	3.0 (1.0)	2.6 (1.0)	0.398	2.1 (0.4)*	2.0 (0.7)**	0.545
Poes, ee (cm H_2O)	−2.0 (3.5)	5.2 (6.9)	0.013	5.4 (3.1)***	14.0 (8.0)**	0.008
Pgas, ee (cm H_2O)	12.1 (6.2)	19.1 (4.7)	0.015	7.1 (2.6)*	14.3 (5.7)*	0.003
Pdi, ee (cm H_2O)	14.1 (5.3)	13.9 (5.1)	0.933	1.7 (2.8)***	0.2 (5.3)***	0.461
P_L, ee (cm H_2O)	2.9 (1.4)	−4.7 (5.0)	<0.001	−4.6 (2.5)***	−11.6 (5.0)***	0.002

Lung volumes, dynamic compliance and end-expiratory pressures at FRC in the thoracic and abdominal compartment for obese and normal subjects, seated and supine.
*p<0.05, **p<0.01, ***p<0.001 for the comparison of associated changes with posture
cdyn, dynamic compliance; FRC, functional residual capacity; Pdi, ee, transdiaphragmatic pressure at end-expiration; Pgas, ee, gastric pressure at end-expiration; P_L, ee, transpulmonary pressure at end-expiration; Poes, ee, oesophageal pressure at end-expiration; TLC, total lung capacity; V_t, tidal volume.

considering that our obese group had a slightly higher BMI (11.5 (2.8) cm H_2O in their data compared with 14.3 (5.7) cm H_2O in obese subjects supine at FRC in our study).

Intra-abdominal hypertension has been identified as an important issue in obesity that potentially impacts on ventilation in the perioperative setting.[32][33] Pelosi et al[24] investigated the respiratory system in sedated and paralysed morbidly obese subjects. They included eight subjects (BMI 48.7 (7.8) kg/m^2) with a similar age (38 (12) years) to our groups and compared respiratory mechanics in supine posture with a historic normal control group. FRC was remarkably reduced in obesity. Changes in mechanical properties secondary to reduced lung volumes were found to be caused by an excessive and unopposed intra-abdominal pressure (24.0 (2.2) cm H_2O), as measured with a transurethral bladder catheter and the bladder being filled with 100 mL of saline solution. However, the study design[24] did not allow them to measure lung volumes simultaneously during wakeful breathing nor did it consider the upright posture. Our study analysed spontaneous respiratory muscle function opposing the high intra-abdominal pressure in non-sedated and non-paralysed spontaneously breathing obese subjects, seated and supine.

Our data confirm differences in compliance related to posture[23][34] and differences in lung volumes associated with obesity and posture.[8][12][19] The mid-range compliance at 50–60% of TLC was not different between the groups, but tended to fall with recumbency. At a higher lung volume of 60–70% TLC, the compliance was reduced in obese subjects,

seated and supine, and tended to fall in this group with recumbency. The difference between the groups was explained, to some extent, by the plateau of the PV curve in the restricted obese subjects when approaching TLC. However, a reduced compliance with change in posture to the supine might be caused by multiple factors, including a drop in lung volumes, the increased impact of abdominal pressures on the thoracic cavity, a change in the chest configuration and an increased venous return. These results provide a likely explanation why patients with obesity benefit from CPAP when supine[12][35]; CPAP counterbalances the high intrathoracic and intra-abdominal pressures and elevates the FRC levels. However, questions regarding the proposed model of lung 'hypoinflation' in obesity remain,[16][18] and further larger studies distinguishing between obese subjects with and without restriction may provide additional insight into the pathophysiological origin of intra-abdominal hypertension and its impact on respiratory function and symptoms in obesity. The variability of the relationship between static and dynamic compliance in obese subjects requires further investigations, including whether or not it could be caused by chronic changes to the small airways or lung parenchyma.

Clinical implications
The impact of obesity, particularly morbid obesity, on the respiratory system has long been observed in the clinical setting. Obese subjects are more breathless and at risk of developing respiratory failure by day and sleep-disordered breathing by

Table 4 Static pressures during maximal inspiratory effort and static expiratory compliance

Parameter	Normal group, seated	Obese group, seated	p Value	Normal group, supine	Obese group, supine	p Value
Poes at TLC (cm H_2O)	−42.8 (10.9)	−34.9 (10.5)	0.140	−43.3 (13.9)	−42.2 (10.7)	0.846
Pgas at TLC (cm H_2O)	28.9 (25.0)	18.1 (10.9)	0.206	28.5 (22.0)	16.4 (13.7)	0.180
Pdi at TLC (cm H_2O)	54.1 (19.5)	50.5 (17.6)	0.682	64.8 (24.0)*	52.7 (16.7)	0.235
$P_{L,max}$ at TLC (cm H_2O)	32.2 (2.8)	23.7 (7.4)	0.033	31.7 (2.5)	25.3 (7.5)	0.028
PImax at FRC (cm H_2O)	109.9 (41.8)	72.2 (30.1)	0.043	96.7 (32.9)*	55.2 (26.0)**	0.009
$C_{L,stat}$ slope 50–60%pred TLC (%pred TLC/cm H_2O)	7.0 (3.4)	6.1 (5.0)	0.682	4.1 (2.0)*	3.6 (2.2)*	0.617
$C_{L,stat}$ slope 60–70%predTLC (%pred TLC/cm H_2O)	8.4 (5.1)	3.8 (1.7)	0.023	6.6 (4.8)	2.9 (1.2)*	0.040

Pressures during full inflation to TLC (IC manoeuvre) and PImax manoeuvre at FRC in obese and normal group, seated and supine. Obese subjects poorly performed the PImax manoeuvres, particularly when supine. The sixth and seventh row are estimates of expiratory static lung compliance ($C_{L,stat}$) over a given range of volume. The mid-range slope between 60 and 70% of TLC could not be measured in one of the obese subjects.
*p<0.05, **p<0.01, ***p<0.001 for the comparison of associated changes with posture.
FRC, functional residual capacity; IC, inspiratory capacity; TLC, total lung capacity.

night compared with their matched peer group. Our findings set out the importance of obesity in the clinical setting in the fields of respiratory, sleep and critical care medicine. In particular, the negative effect of the supine posture should be considered when assessing the bed-bound patient or deciding ventilator settings.

Hypothetically, it could be speculated that interventions that reduce intra-abdominal pressures would improve respiratory function in the obese, with an impact on sleep-disordered breathing, breathlessness and respiratory failure, as well as reducing perioperative risks.

Our findings may also provide an explanation for an observation that occurs with increasing frequency in our clinical practice. Specifically the authors have seen overweight patients with seated hypoxia and restrictive defects where the a-A gradient narrows with exercise. We speculate that such patients are moved, as the minute ventilation increases, to a steeper part of the PV curve, thus improving ventilation–perfusion matching. This is consistent with the findings by O'Donnell *et al* that the exercise capacity of severely obese patients is less impaired than expected.[9] Such findings are important in the context of exercise rehabilitation programmes for patients with severe obesity.

Critique of the method
Careful matching is essential in studies with small groups. We sought to compare similar groups with regard to age, gender and height. There were small differences in lung volumes, and it could be argued that expressing all lung volumes as per cent predicted could be more helpful for data presentation. However, this is difficult because there are no standard reference volumes for supine posture that could have been used. We have therefore chosen to describe volumes in absolute units (L) and, where appropriate, in per cent predicted. Nonetheless, we appreciate that the gender difference in lung volumes, with lower expected TLC in females, may have led to the assumption that there is no gender difference in dynamic compliance between our groups. To address this limitation for which our study was not powered, we have presented the PV slopes for each individual male and female subject (see online supplementary figures E1 and E2). We accept that larger studies may be required to fully address the relationship between obesity and dynamic compliance. In addition, extreme or morbid obesity has not been explicitly considered when generating reference equations for lung volumes and the current obesity rates in the UK would impact on what is considered 'normal lung function'; approximately 25% of adults in the UK are obese. This explains why existing reference equations might need to be interpreted with caution if they have not been updated; the respective cohort (eg, ECCS) might have evolved, an effect called the 'cohort effect'.

This study focused on pressure gradients as the driving force for lung inflation. To our knowledge, absolute pressures and pressure gradients do not require correction or normalisation in a different way than has been achieved by matching our groups and, therefore, the impact of small differences between the groups in height and lung volumes may be less important.

The measurement of PImax is a volitional manoeuvre and the results, indicating that obese subjects may have been weaker, have to be interpreted with caution, particularly because previous studies failed to show a difference.[12] In the current dataset, although obese subjects were weaker than expected, they were not weak compared with published data.[25][30] The PV curves indicated available pressure generation capacity when TLC was reached in the obese, which makes it unlikely that restriction is caused by weakness. Therefore, the specific cause for the restriction in TLC observed in the obese remains unclear.

Conclusion
Increased intra-abdominal pressure and the consequent increased intrathoracic pressure in obese subjects reduce FRC and ERV. In consequence, patients must either limit V_t or breathe on a less compliant part of the PV curve, thereby increasing their work of breathing, which is already elevated due to the inspiratory threshold load caused by high intrathoracic pressures. The reduced FRC and ERV is an important abnormality of pulmonary mechanics in obesity.

The clinical management of severely obese patients is helped by our increased understanding of intra-abdominal hypertension and the associated reduced lung volumes.

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Observational study of the effect of obesity on lung volumes

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Patients and Methods

Anthropometric Data

Age and gender were recorded. Height, using a wall mounted stadiometer (range 600-2100mm), and weight, using a medical scale (capacity 300kg), were measured. Body-Mass-Index (BMI) was calculated as weight (kg) / height (m)^2. Neck, waist and hip circumference were measured using a standard medical tape measure. Waist-to-hip ratio was calculated as waist (cm) / hip (cm). The thickness of the skin was assessed using a caliper to measure a double skin fold at the level of the umbilicus. The sagittal diameter at the level of the umbilicus was obtained with the help of a spirit level and a bed-mounted ruler in supine posture. Change of the sagittal diameter was recorded when inflating the lungs to TLC.

Lung Function Measurement

The patients underwent standard spirometry and lung volume measurement using the multibreath helium dilution method according to international guidelines (1, 2). Spirometry was performed on a Vitalograph Gold Standard® (Vitalograph®,

Buckingham, UK). We measured lung volumes using a closed-circuit multi-breath helium dilution method on a Jaeger Masterscreen PFT system (Cardinal Health Ltd, Basingstoke, UK) which included a software-based integrator (JLAB software version 4.0). Predicted values were derived from published data for Caucasians (2).

Dynamic Compliance

Dynamic compliance, as used in this study, was calculated as the volume change divided by oesophageal pressure (Poes) change during a normal inspiration (ΔVolume (L) / Δ Poes (cmH$_2$O)). Both parameters were measured when flow was zero, as derived from a pneumotachograph. Oesophageal pressure was taken as a surrogate marker for pleural pressure (3).

Pressure Measurement

We used commercially available, single-use balloon catheters (Cooper Surgical, Trumbull, CT, USA) to measure Poes and Pgas (4). In combination with appropriate volumes of air inside the balloon catheters (0.5ml of air in the oesophageal and 2.0ml of air in the gastric balloons) (5-7). Correct placement of the oesophageal balloon catheter was confirmed as described by Baydur *et al* (8) when seated and supine. The correct placement of the gastric balloon was confirmed by pushing the abdomen slightly from the outside, performing sniff and cough manoeuvres and comparing the signal to the oesophageal balloon recordings. Breathing through a flanged mouthpiece (Hans Rudolph, KA/USA), mouth pressure (Pmouth) was obtained. Inspiratory Poes, and similarly the transducted inspiratory Pmouth are surrogate markers for intrathoracic pressure and indices of global inspiratory muscle contraction (9). Transdiaphragmatic pressure (Pdi) is a measure of diaphragm specific contraction

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(10) and was recorded online, derived from the electronic subtraction of oesophageal from gastric pressure (Pdi=Pgas-Poes). Transpulmonary pressure (P_L) was also calculated (P_L=Pmouth-Poes).

Electromyogram (EMG) of parasternal intercostal and external oblique muscles

The EMG of the parasternal intercostals and abdominal muscles were recorded using surface electrodes (Kendall Arbo®, Tyco Healthcare®, Neustadt, Germany) from standard positions. For recording the EMG of the parasternal intercostals (EMG_{para}) electrodes were placed on each side of the sternum 3cm from the midline in the second intercostal space (11, 12). For the purpose of recording the EMG from the external oblique unilaterally ($EMG_{abdomen}$, recorded from the right side) one electrode was placed in the middle of a vertical line connecting the lower rib cage with the anterior superior iliac spine, with the subject standing. A second electrode was placed approximately 4-5cm anterior to that location, as described by Lasserson *et al* (13). The recordings of the spontaneous EMG, and the respiratory pressures, were sampled at 2kHz, and EMG data were filtered (band-pass filter 30 Hz - 1,000 Hz).

Maximal inspiratory mouth pressure (PImax)

Maximum inspiratory pressures were measured from functional residual capacity in the standard way (14, 15), with the patient seated, wearing a nose-clip and using a flanged mouthpiece (P.K. Morgan Ltd®, Rainham, UK). Repeated efforts were made, until consistent results were achieved, and the numerically largest (i.e. most negative) pressure noted. The average of the pressure was measured over one second (14).

Sample Size Calculation

We used published data from a previous study with obese subjects to calculate sample size (16). The probability was 80 percent (P=0.8) that the study would detect a treatment difference at a two-sided 0.05 significance level with a total of 18 subjects (in two arms), if the true difference between the pressures (end-expiratory oesophageal pressure, Poes, ee) was 6.0 cmH$_2$O. This was based on the assumption that the standard deviation of the response variable (Poes, ee) was 4.2 cmH$_2$O.
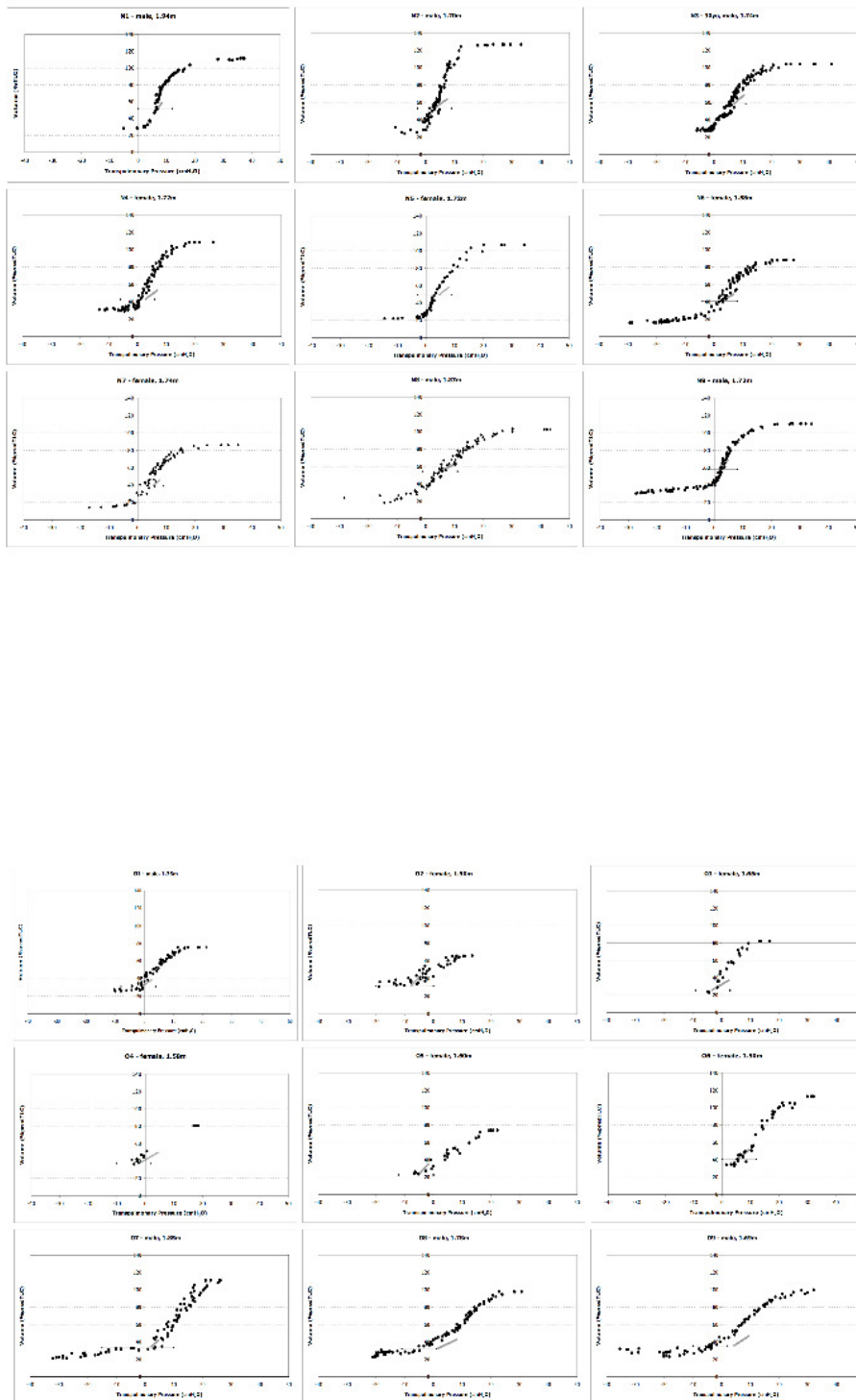
Results

Figure E1: Pressure-Volume curves in seated normal (upper panel) and obese (lower panel) subjects were adjusted to percent predicted TLC to account for gender and height. The slope is steeper in the non-obese subject, determining compliance. Obese subjects breathe at lower FRC levels and when corrected for lung volume, age and gender there is a similar dynamic compliance in obese and non-obese subjects. Transpulmonary pressures during tidal breathing become more negative the more restricted the patient is. Obese subject ´O4´ did not produce satisfactory breathing manoeuvres over the entire expiratory range and only the maximal and minimal pressures were noted. Horizontal bars indicate FRC, short diagonal gray bars indicate tidal breathing.
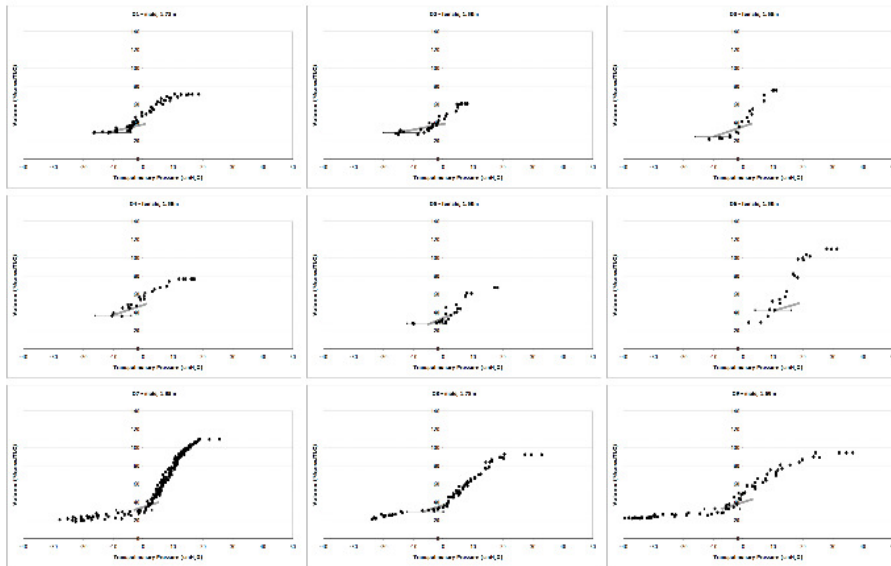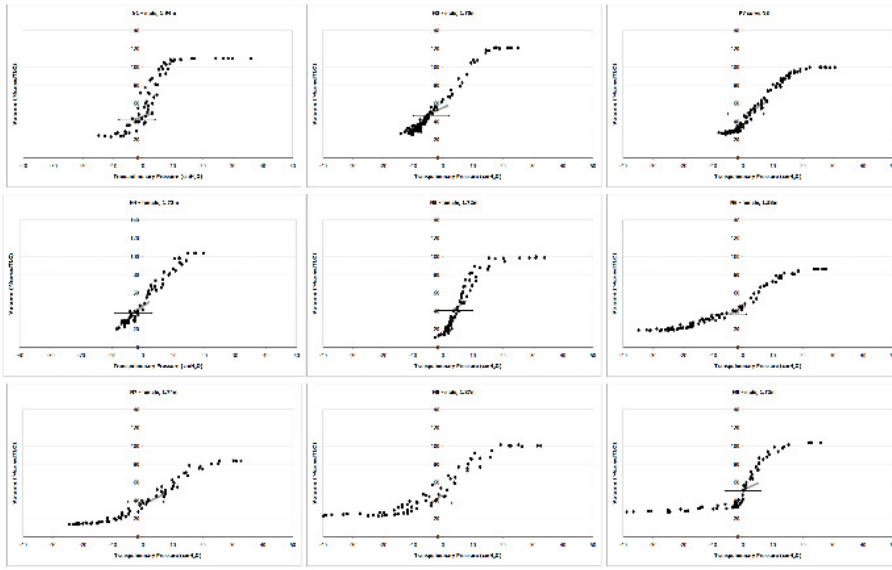
Figure E2: Pressure-Volume curves in supine normal (upper panel) and obese (lower panel) subjects were adjusted to percent predicted TLC when seated, as there are no reference values for supine posture related TLC, to account for gender and height. Obese subjects breathe at low FRC. Subjects ´O2-O5´ had suboptimal breathing manoeuvres and their PV curves should be interpreted with caution.

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