Cardiopulmonary effects of the volume recruitment manoeuvre in infant swine

David L. Shulman MD CCFP, George A. Volgyesi PEng,
Jerrold Lerman MD FRCPC, Sandra J. England PhD, A.
Charles Bryan MBBS PhD FRCPC

The volume recruitment manoeuvre is a non-invasive technique used to measure respiratory mechanics in infants. Because airway pressure increases during this manoeuvre, lung volume, compliance and cardiac output may change. In order to assess possible changes in cardiopulmonary function caused by the volume recruitment manoeuvre, we applied this technique to seven intubated infant swine breathing spontaneously during anaesthesia with halothane and N₂O. Tidal volume (V_T), respiratory frequency, arterial blood gases, cardiac output (CO) and total respiratory compliance were measured before and after the manoeuvre. In three swine functional residual capacity (FRC) was measured by helium dilution before the manoeuvre, and in four swine diaphragmatic EMG was recorded continuously. Finally, all swine were paralysed during volume recruitment to assess the contribution of the respiratory muscles to post-manoeuve respiratory mechanics. V_T and f increased immediately after the manoeuvre but there were no significant changes in PaCO₂, or alveolar to arterial oxygen gradient. There was a small but statistically significant decrease in CO. Compliance increased by 17.8 ± 3.6 per cent and FRC increased by a mean of 41.1 ml (or 51.9 per cent increase above the baseline FRC). The increase in FRC could not be explained by active mechanisms since the diaphragmatic EMG showed no post-inspiratory activity and neuromuscular paralysis did not decrease FRC. We conclude that the volume recruitment manoeuvre increases FRC and compliance by recruiting collapsed alveoli, and this effect must be taken into consideration when applying this test to infants.

Key words

ANESTHETICS, VOLATILE: halothane; LUNG: mechanics; functional residual capacity, compliance.

From the Departments of Anaesthesia and Respiratory Physiology and the Research Institute, The Hospital for Sick Children and the University of Toronto, Toronto, Canada.

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Address correspondence to: Dr. D. Shulman, The Department of Anaesthesia, The Hospital for Sick Children, 555 University Ave., Toronto, Ontario, Canada M5G 1X8.

Functional residual capacity (FRC) decreases during general anaesthesia. This may be attributed, in part, to a loss of volume from atelectatic units in the dependent regions of the lungs.¹ Loss of lung volume may account for the increase in shunt which accompanies general anaesthesia.² Westbrook *et al.*³ found that the decrease in FRC leads to a decrease in lung compliance and proposed that elevating lung volume would restore compliance towards its pre-anaesthetic level. It has been suggested that positive airway pressure might counter the decrease in FRC during anaesthesia. However, positive end-expiratory pressure (PEEP) in anaesthetized subjects with normal cardiorespiratory function decreases cardiac output.² As well, PEEP applied to dogs decreased static and dynamic lung compliance in spite of an increase in lung volume.⁴ This decrease in compliance was reversible by the application of sighs. As a result of these considerations, positive airway pressure has not found wide application in anaesthesia.

Periodic sighs increase lung compliance as shown in dogs by Mead and Collier⁵ and in humans by Bendixen *et al.*⁶ However, Nunn *et al.*⁷ and Douglas *et al.*⁸ were unable to confirm the increase in compliance with sighs. The differences in their results may be due to different protocols for sigh frequency, duration and plateau pressure attained. Even if periodic sighing were proved to be effective, this modality would be restricted to intubated subjects because sighs require high airway pressures.

A new, non-invasive technique which we termed "volume recruitment" has been introduced for measuring respiratory mechanics in spontaneously breathing animals and infants.⁹ In this technique lung volume increases during spontaneous inspiration while expiration is occluded for three or four breaths. It offers the advantage that it may be performed by either mask or tracheal tube. Although this technique has been applied to neonates with and without lung disease with no apparent deleterious effects,⁹ the changes in FRC, compliance, gas exchange and cardiac output have not been reported. We therefore applied the volume recruitment manoeuvre to seven anaesthetized infant swine in order to investigate its cardiopulmonary effects.

FIGURE 1 Apparatus for the volume recruitment manoeuvre in intubated infant swine. See text for details.

Methods

With approval of the local animal care committee, seven infant swine, 2.8 to 7.0 kg, ten days to three weeks of age, were studied. After an overnight fast, the swine was positioned supine under an overhead radiant heater to maintain body temperature. Anaesthesia was induced with halothane in a 2:1 mixture of N_2O and oxygen. A cuffed 3.5 mm tracheal tube was inserted following application of lidocaine spray to the larynx. Anaesthesia was maintained with a halothane/ N_2O/O_2 mixture delivered via a Bain circuit. Ventilation was spontaneous and positive airway pressure was avoided before the manoeuvre. The end-tidal concentration of halothane, as determined by infrared analysis, was maintained between 0.7 and 1.23 per cent. The ECG was continuously monitored. The femoral artery and vein were cannulated with 5 Fr. feeding catheters, and the arterial blood pressure was measured via a transducer (Statham 2306). Lactated Ringer's solution, 20 ml $\cdot$ kg⁻¹ body weight was infused before the study commenced. Airway pressure was measured through a side port on the tracheal tube connector (Honeywell 142PCO1G). A heated size O pneumotachograph (Hewlett Packard 47303A digital pneumotachograph) was connected to the tracheal tube. The flow ($\dot{V}$), volume (V) and airway pressure (P) signals were recorded on magnetic tape and the V, P, BP and ECG signals were recorded on a Gould 8188 strip chart recording system. A Y-shaped apparatus (Rudolph 1530), with two valves to ensure unidirectional flow of gas, was connected to the pneumotachograph. The Bain circuit was connected to the inspiratory port of the apparatus such that

fresh gas flow entered the inspiratory port and expiratory gas was vented to the room via the expiratory port (Figure 1). During spontaneous breathing the expiratory port of the apparatus was occluded at end inspiration. Expiration was therefore occluded and the V and P signals rose to a plateau (Figure 2). During the following unimpeded inspiration, volume increased above the tidal volume range and the subsequent expiration was again occluded. Following three breaths the occlusion was released at mid-expiration and tidal breathing resumed (Figure 2).

From two to seven manoeuvres were carried out in each swine. The following measurements were made prior to and immediately after each manoeuvre: tidal volume (V_T) and frequency (f), $PaCO_2$, and the arterial to alveolar oxygen gradient ($D(A-a)PO_2$) calculated using the alveolar gas equation from arterial blood and end-tidal gas (Corning 175 automatic gas analyser). The analyser underwent calibration with known gas mixtures (Linde Mixed Medical Gas primary standards) no more than one-half hour before the measurement and had mean 1.5 per cent coefficient of variation (CV) for repeated PO_2 determinations and 3.0 per cent CV for PCO_2 . In six swine cardiac output (CO) using a dye dilution technique (indocyanine green) was also determined before and after each manoeuvre. The change in end-expiratory volume was measured from the paper record. In four swine, total respiratory compliance was measured by the passive flow-volume (PFV) manoeuvre of LeSouef *et al.*¹⁰

In three swine functional residual capacity (FRC) was measured by closed circuit helium dilution in triplicate prior to the first volume recruitment manoeuvre.

FIGURE 2 Volume (V_t) and pressure (P) signals from an infant swine during the volume recruitment manoeuvre. Expiration is occluded while the subject progressively recruits volume during three unoccluded inspirations. V_t and f increase following the release of the occlusion while there is no change in the blood pressure (BP) or in the ECG. Blood sampling resulted in the interruptions in the BP signal.

Diaphragmatic EMG was measured from two electrically isolated electrodes sewn into the costal diaphragm through a small midline epigastric laparotomy. The signals were relayed through an isolated EMG preamplifier and a medium gain amplifier (Coulbourn S75 04B) with audio amplifier. The signal was recorded on magnetic tape and subsequently electronically processed to a moving time average (MTA).¹¹ Diaphragmatic EMG was recorded throughout the test period in these swine.

During the last volume recruitment manoeuvre but prior to the release of the occlusion, the swine was paralysed by rapidly infusing IV vecuronium ($0.5 \text{ ml} \cdot \text{kg}^{-1}$). Twenty seconds after the release of the expiratory occlusion controlled ventilation was initiated. The swine was then killed with an overdose of a barbiturate.

Statistical significance ($P < 0.05$) was determined using the Wilcoxon signed rank test with each swine as its own control.

Results

V_t and f increased significantly after the volume recruitment manoeuvre (Table I). PaCO_2 did not increase significantly following the manoeuvre, and there was no significant change in D(A-a)PO_2 . Mean baseline CO was $0.22 \text{ L} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ and CO decreased to a small but significant extent ($p = 0.02$).

Mean baseline compliance was $1.7 \pm 0.6 \text{ ml} \cdot \text{cm H}_2\text{O}^{-1} \cdot \text{kg}^{-1}$. Following the volume recruitment manoeuvre, compliance increased by a mean of 17.8 ± 3.6 per

cent over baseline. In one swine in whom the compliance measurements were repeated at 20 sec intervals following the manoeuvre, compliance gradually decreased towards baseline over the subsequent 2.5 minutes (Figure 3). FRC increased by a mean of $41.1 \pm 18.1 \text{ ml}$. In the three swine in whom FRC was measured by Helium dilution, the mean increase in FRC was 51.9 per cent (Table II).

The diaphragmatic EMG demonstrated inspiratory activity but no post-inspiratory activity either before or after the volume recruitment manoeuvre (Figure 4). After paralysis, post-release FRC was similar to that attained after the manoeuvres carried out during spontaneous ventilation (Figure 5).

The mean duration of the manoeuvre was 29.4 sec with the range from 14.5 to 56.8 sec.

Discussion

The volume recruitment manoeuvre increased FRC by 41.1 ml in seven infant swine during halothane anaesthesia. We believe that this increase was probably due to recruitment of alveoli which are atelectatic during halothane anaesthesia. On the other hand, it is possible that the increase in FRC results from an active mechanism in which post-inspiratory activity of the inspiratory muscles or expiratory braking in combination with a short expiratory time could result in dynamic elevation of FRC. However, we found that there was no post-inspiratory activity of the diaphragm following the manoeuvre (Figure 4). In addition, the increase in FRC was also

Compliance

FIGURE 3 Total respiratory compliance measured prior to the volume recruitment manoeuvre as the baseline and every 20 sec for 160 sec following the manoeuvre.

present during muscle paralysis with vecuronium (Figure 5), thus confirming the lack of an effect of the inspiratory muscles on FRC after the manoeuvre. Therefore the increase in FRC following the manoeuvre is the result of recruitment of alveoli, and this is accompanied by an increase in compliance. Gradual derecruitment of lung volume was demonstrated in one swine by the gradual decrease in compliance to its pre-manoeuvre value over 2.5 minutes following the manoeuvre (Figure 3).

The volume recruitment manoeuvre itself has been used to measure compliance in human infants⁹ by promoting sufficient volume increase to construct a volume-

pressure (V-P) curve. Compliance was then the cord to any point on the curve.⁹ Bradypnoea during a manoeuvre was not noted in their study, and up to five inspirations were used. We noted a marked bradypnoea during the manoeuvre in the infant swine of the present study, and therefore we only permitted three inspirations before release of the occlusion. As a result of allowing only three inspirations in the present study, there were not sufficient data points and not enough range of volume to construct and analyze a V-P curve. Therefore, compliance was measured here using the technique described by LeSouef *et al.*¹⁰

TABLE I Cardiopulmonary function before and after the volume recruitment manoeuvre in seven anaesthetized infant swine (means ± SD)

	V_T (ml)	f (breaths·min ⁻¹)	$PaCO_2$ (torr)	$D(A-a)PO_2$ (torr)	$\dot{CO}$ (l·min ⁻¹)
Before	30.1 ± 11.7	30.6 ± 15.9	53.2 ± 14.2	112.0 ± 34.7	1.03 ± 0.37
After	36.8 ± 15.8*	32.4 ± 15.1*	57.8 ± 13.9	114.7 ± 42.1	0.97 ± 0.36*

*P < 0.05 compared with before measurement.

FIGURE 4 Volume, flow, diaphragmatic EMG, and moving time average (MTA) before, during and after the volume recruitment manoeuvre in one infant swine. Note the EMG and MTA signals during inspiration with no post-inspiratory activity.

FIGURE 5 Volume signal during a volume recruitment manoeuvre. At the beginning of the third occluded expiration vecuronium was administered. Respiratory movements were lost shortly following the release of the occlusion, but there was no change in the postmanoeuvre FRC. Note the change in recording speed after the first ten breaths.

TABLE II Increase in FRC in three infant swine

Number	Baseline FRC (ml)	Increase in FRC (ml)	% Increase
7	99.6	62.5	62.6
8	105.5	63.6	60.3
9	106.4	35.0	32.9
mean	103.7	53.7	51.9

The mean compliance for the infant swine in this study ($1.7 \text{ ml} \cdot \text{cm H}_2\text{O}^{-1} \cdot \text{kg}^{-1}$) was similar to that reported in a study of healthy newborn swine during anaesthesia ($1.77 \pm 0.41 \text{ ml} \cdot \text{cm H}_2\text{O}^{-1} \cdot \text{kg}^{-1}$).¹² As well, CO was within the normal limits for our laboratory. Therefore the infant swine in this study were normovolaemic or suitably compensated. This is important since the application of positive airway pressure may have more deleterious effects in subjects who are unstable haemodynamically.

Mead and Collier⁵ demonstrated that a controlled

hyperinflation of the lungs to a peak airway pressure of 40 cm H₂O for 10 sec increased compliance and FRC, and postulated that this was due to recruitment of atelectatic lung units in the dependent regions of the lung. Subsequent studies in anaesthetized man have shown a variable effect of hyperinflation on compliance,^{4,6-8} but in none of these studies were measurements made of the effects of hyperinflation on FRC or on haemodynamic variables. The different protocols used had in common an increase in airway pressure to 20 to 40 cm H₂O for up to 40 sec. These prolonged periods of high airway pressure may have reduced CO and this may be the explanation for the failure to demonstrate improvement in D(A-a)PO_2 . In none of the above cited studies was CO measured, but in one study the authors stated that "hyperinflation caused severe cardiovascular disturbances" including the disappearance of the pulse and blood pressure during the inflation and their return following resumption of normal breathing.⁷

We speculated that these profound changes in CO

caused by hyperinflation could be minimized or eliminated by maintaining spontaneous breathing and by limiting the airway pressure attained during the manoeuvre. The higher airway pressure is only applied intermittently and spontaneous breathing continues throughout the manoeuvre, thereby avoiding the prolonged decrease in right ventricular preload which is found with continuous positive airway pressure. In fact, we found a slight decrease in CO following the volume recruitment manoeuvre and this was without physiological significance since heart rate, blood pressure and arterial blood gas tensions were unchanged throughout the manoeuvre.

The volume recruitment manoeuvre has been applied to infants as a test of respiratory mechanics, and the volume-pressure curve obtained was curvilinear with the convexity of the curve toward the pressure axis.⁹ This suggests that volume recruitment increases compliance in infants also. Since the volume recruitment manoeuvre caused minimal physiological disturbance in this study, and has the potentially beneficial effects of increasing FRC and compliance during anaesthesia, its further application to anaesthetized humans should be considered.

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Résumé

Le « recrutement de volume » est une méthode de mesure atraumatique de la mécanique respiratoire des bébés. L'augmentation de la pression des voies aériennes qu'elle entraîne peut modifier la compliance et le volume pulmonaire ainsi que le débit cardiaque. C'est pour évaluer ces changements que nous avons appliqué la technique à sept cochonnets intubés respirant halothane-O₂-N₂O. Nous avons mesuré le volume courant (V_T), la fréquence respiratoire (f), les gaz artériels, le débit cardiaque (DC) et la compliance pulmonaire totale avant et après le recrutement. Par dilution d'hélium, nous avons évalué la capacité résiduelle fonctionnelle (CRF) avant la manoeuvre chez trois sujets et avons enregistré en continu l'EMG diaphragmatique des quatre autres. Enfin, nous avons isolé la contribution musculaire aux changements mécaniques en paralysant les cochons pendant une session de recrutement. Immédiatement après la manoeuvre, nous avons observé une augmentation du V_T et de f, sans changement de la PaCO₂ ni du gradient alvéolo-artériel en oxygène. La petite diminution du DC était statistiquement significative alors que la compliance croissait de 17,8 ± 3,6 pour cent et la CRF augmentait en moyenne de 41,1 ml à 151,9 pour cent des valeurs contrôles. Vu l'absence d'activité post-inspiratoire à l'EMG et l'influence nulle de la paralysie sur l'augmentation de la CRF, on peut conclure à la nature passive de ce phénomène. Les changements de la CRF et de la compliance s'expliquent par du recrutement alvéolaire et cela doit être pris en considération quand on applique ce test chez l'enfant.