Comparison of central venous, oesophageal and mouth occlusion pressure with water-filled catheters for estimating pleural pressure changes in healthy adults

A. Flemale*, C. Gillard**, J.P. Dierckx**

ABSTRACT: The validity of the central venous and water-filled oesophageal catheter technique as a measure of pleural pressure changes was tested in ten healthy subjects in different body positions during inspiratory efforts with occluded airways, by comparing the simultaneous changes in mouth pressure (ΔPm) taken to represent pleural pressure changes, in central venous pressure (ΔPcv) and in oesophageal pressure (ΔPoes). ΔPcv/ΔPm values were close to unity in the sitting and left lateral positions, whereas in the supine and right lateral position, substantial deviations from unity were found in some instances. ΔPoes/ΔPm values were close to unity in all positions, except some rare instances. No appreciable phase difference between ΔPm/ΔPoes and ΔPm/ΔPcv was found when the amplitude ratios were close to unity. We conclude that valid measurements of pleural pressure changes can be obtained in most instances with the central venous and the water-filled oesophageal catheter system according to the occlusion test procedure.

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Interest in the measurement of the mechanical lung properties in critically ill patients is due to the fact that several causes may lead to, or aggravate, respiratory distress, and prompt diagnosis and treatment may be of the utmost importance. The measurement of the total respiratory compliance in controlled ventilation may be useful in several cases but, sometimes, it may be insufficient due to a modification of the chest wall compliance following, for instance, abdominal distension, peritonitis or pleural effusion [4, 10]. The measurement of the transpulmonary pressure changes (ΔPtp) is then mandatory for the partitioning of the total respiratory mechanics into lung and chest wall components. The study of lung mechanics during assisted or spontaneous ventilation, also implies the measurement of ΔPtp. However, in the supine position, the validity of the oesophageal balloon technique has been questioned [11, 12]. Static inspiratory and expiratory efforts with an open glottis and a closed external airway (Mueller and Valsalva manoeuvres) and, more recently, the occlusion test have been proposed to validate this technique. Equal changes in oesophageal (ΔPoes) and in the mouth (ΔPm) pressures during these manoeuvres indicate that changes in oesophageal pressures provide a valid estimate of changes in pleural surface pressure [14]. The occlusion test, where ΔPoes and ΔPm during spontaneous inspiratory efforts against a closed external airway are compared, does not require the collaboration of the subject and has been used in neonates [3, 15] and awake and anaesthetized adults [2, 7]. Studying acutely ill patients with chronic obstructive pulmonary disease, who were either intubated or breathing via a tracheostomy, no discrepancy was observed between oesophageal and tracheal occlusion pressures. However, the patients were studied in the semirecumbant posture [16].

Oesophageal (Poes) and central venous pressure (Pcv) have already been compared and Pcv has been found more accurate and reliable than Poes as a reflection of Ptp in the anaesthetized patients [17].

In this study, we have compared simultaneous measurements of central venous pressure changes (ΔPcv), ΔPoes and ΔPm during occlusion tests, using fluid-filled catheters to obtain similar frequency response characteristics with the three systems (Poes, Pm, Pcv). For this purpose, healthy adults have been studied in seated, supine, right lateral and left lateral positions.

Material and methods

We have studied ten normal volunteers (8 men and 2 women) with a mean age (±SD) of 31±6 yr, a mean (±SD) vital capacity of 4.8±0.9 l (97±3% of predicted) and a mean (±SD) forced expiratory volume in one second (FEV1) of 3.9±0.9 (101±3% of predicted) [5].

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Mouth (Pm), oesophageal (Poes) and central venous pressure (Pcv) were measured using similar polyethylene catheters (Vygon, internal diameter of 1.5 mm and length of 75 cm). Each catheter was connected to similar pressure transducers (Bentley Trantec, M800). Each system was filled with water and kept free of bubbles by flushing with water between measurements. These systems have been tested with a sine-wave pressure generator and a square-wave of pressure and the frequency response was flat in both magnitude and phase to more than 20 Hz (see Appendix).

Flow changes at the mouth, observed for verifying the effectiveness of the occlusion of the airways, were measured with a Lilly pneumotachograph, connected to a DP-45 Validyne differential pressure transducer.

Pm was sampled from a lateral port at the distal end of the mouthpiece. A tap attached to the pneumotachograph was used to occlude the airway opening. All signals were amplified (Heres, ACEC, Belgium) and recorded on an eight-channel recorder (Gould, Brush).

In five subjects, mouth vs either oesophageal pressure or central venous pressure was displayed on a Tektronix storage oscilloscope and photographs were taken using a Tektronix polaroid camera during the occlusion tests. Phase differences between Pcv and Pm were obtained using the ratio between the horizontal width of the loops at midpoint with the total horizontal deflection (method of Lissajous curves). Calibrations for pressure were done before and after each experiment.

Procedure

A catheter was introduced transcutaneously via an antecubital vein and was positioned into the superior vena cava under fluoroscopic control. In case of positioning into the right ventricle, the catheter was withdrawn until the ventricular waves disappeared. After topical anaesthesia of the nasal mucosa and pharynx with Lidocaine, another catheter was passed transnasally into the stomach and then gradually withdrawn until a negative deflection was present during inspiration. The catheter was then withdrawn another 10 cm and secured at that level.

The occlusion test was performed by occluding the external airway at the end of expiration and simultaneously recording the oesophageal, mouth and central venous pressure changes during the following five spontaneous occluded inspiratory efforts. This manoeuvre was repeated several times at about 0.5 Hz and the amplitude of the pressure changes was about \( \pm 20 \text{cmH}_2\text{O} \). In five subjects (Nos 1–5) the tests were performed in the sitting, supine, right and left lateral positions. In the five other subjects (Nos 6–10) the tests were performed in the sitting and supine positions only.

The contractions of the heart caused important changes in Pcv and minor changes in Poes. The magnitude of these artefacts was measured in each subject position. In some cases a reduction of the cardiac artefacts was obtained by withdrawing the central venous catheter 10–15 cm from its initial position. Statistical significance was tested using the paired t-test. All the values for the different groups are means and standard deviations (sd).

Results

Representative records of occlusion tests obtained in a subject in different positions are shown in figure 1. The changes in Pcv, Poes and Pm were virtually the same throughout the occluded periods in all postures, except in the right lateral decubitus positions where the changes in Pcv were reduced.

A similar result is shown in figure 2, which depicts a tracing of \( \Delta \text{Pcv} \) vs \( \Delta \text{Pm} \) obtained on the oscilloscope during an occlusion test. The relationship is linear with the slope close to unity, the deviation from the line of identity representing cardiac artefacts.

The ratios between the swings in central venous, oesophageal and mouth pressure during the occlusion test for the different body positions are shown in table 1, II and III and the values of the pressure swings are shown in figure 3. Each individual value is the mean of ten measurements.

Comparisons of Pcv and Pm

In sitting and left lateral positions, all individual ratios, as well as the mean ratio, were close to unity. On the other hand, in the supine position \( \Delta \text{Pcv}/\Delta \text{Pm} \) was substantially less than unity in three subjects.

Table I. The \( \Delta \text{Pcv}/\Delta \text{Pm} \) ratios during the "occlusion test" in ten subjects

<table>
<thead>
<tr>
<th>Subjects</th>
<th>sitting</th>
<th>supine</th>
<th>right lateral</th>
<th>left lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.04</td>
<td>0.87</td>
<td>1.04</td>
<td>0.99</td>
</tr>
<tr>
<td>2</td>
<td>1.04</td>
<td>0.97</td>
<td>0.96</td>
<td>1.04</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>0.95</td>
<td>0.53</td>
<td>1.06</td>
</tr>
<tr>
<td>4</td>
<td>1.09</td>
<td>1.05</td>
<td>1.05</td>
<td>1.11</td>
</tr>
<tr>
<td>5</td>
<td>0.92</td>
<td>0.87</td>
<td>0.98</td>
<td>1.12</td>
</tr>
<tr>
<td>6</td>
<td>1.03</td>
<td>1.04</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>7</td>
<td>0.96</td>
<td>0.95</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>8</td>
<td>1.04</td>
<td>0.65</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>9</td>
<td>0.99</td>
<td>0.70</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>10</td>
<td>1.03</td>
<td>0.61</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Mean</td>
<td>1.01</td>
<td>0.86</td>
<td>0.90</td>
<td>1.06</td>
</tr>
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</table>

±sd 0.04 0.16 0.2 0.05

*Each value is the mean of ten measurements. --: not measured;
Subjects 3, and 6: Pcv catheter withdrawn 10 cm from its initial position. Subjects 5 and 10: PCV catheter withdrawn from 15 cm.
Fig. 1. Representative tracings of flow (V), central venous (Pcv), oesophageal (Poes) and mouth (Pm) pressures during an occlusion test in sitting, supine, right and left lateral positions. Time from right to left. Subject 3.

There was no statistical difference between the pressure swings in the different positions, except for the right lateral positions where there was a small but significant difference (p = 0.04).

The phase differences between ΔPcv and ΔPm during the occlusion test were close to zero in all instances for the five subjects studied (ranging between +5° and -5°), except for subjects 8-10 in the supine position where a phase lag of more than 20° was observed.

Changes of Pcv due to cardiac artefact are listed in Table IV and are expressed in percent on corresponding ΔPm.

Comparisons of Poes and Pm

In all the positions studied, the individual ratios were close to unity except for one subject in the sitting
Fig. 3. Comparison of pressure swings recorded with the mouth (ΔPm), with the central venous (ΔPcv) and with the oesophageal (ΔPoes) catheters during occlusion tests, in seated, supine, right and left lateral decubitus positions. Interrupted line is the line of identity. Each value is the mean of ten measurements.

**Table II. The ΔPoes/ΔPm ratios during the occlusion test in ten subjects**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sitting</th>
<th>Supine</th>
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<th>Left Lateral</th>
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</thead>
<tbody>
<tr>
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<td>1.03</td>
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<td>1.10</td>
<td>1.02</td>
</tr>
<tr>
<td>2</td>
<td>0.98</td>
<td>0.97</td>
<td>1.01</td>
<td>0.99</td>
</tr>
<tr>
<td>3</td>
<td>1.02</td>
<td>1.16</td>
<td>1.01</td>
<td>1.01</td>
</tr>
<tr>
<td>4</td>
<td>1.13</td>
<td>1.02</td>
<td>1.03</td>
<td>1.06</td>
</tr>
<tr>
<td>5</td>
<td>0.90</td>
<td>0.84</td>
<td>1.01</td>
<td>0.99</td>
</tr>
<tr>
<td>6</td>
<td>0.98</td>
<td>1.06</td>
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<tr>
<td>7</td>
<td>0.97</td>
<td>1.01</td>
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<tr>
<td>8</td>
<td>0.96</td>
<td>1.02</td>
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<tr>
<td>9</td>
<td>1.02</td>
<td>1.08</td>
<td></td>
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<tr>
<td>10</td>
<td>1.02</td>
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<td>1.01</td>
<td>1.03</td>
<td>1.01</td>
</tr>
<tr>
<td>±SD</td>
<td>0.06</td>
<td>0.09</td>
<td>0.03</td>
<td>0.18</td>
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*Each value is the mean of ten measurements. – : not measured.

Position (No. 4) and two subjects in the supine position (Nos 3 and 5). We could not obtain a better ratio by repositioning the oesophageal catheter in any of these cases. The group average in ΔPoes/ΔPm was close to unity in all body positions. There was no statistical difference between the pressure swings in the different positions.

The phase difference between the ΔPoes and ΔPm during the occlusion tests was close to zero in the five subjects studied in the seated and supine positions (Nos 6–10), the relationships being virtually superimposed on a breath-by-breath basis.

We have not observed oesophageal spasms after insertion of the catheter which was performed very easily. A small cardiac artefact was sometimes present but was considerably less than with Pcv. These artefacts never exceeded 3 cmH₂O and rarely hindered the measurement of the ΔPoes/ΔPm ratios because of the greater amplitude of the total swings (about 20 cmH₂O).

**Comparisons of Poes and Pcv**

In all positions studied, the individual ratios were close to unity, except for three subjects in the supine position (Nos 8–10) and one subject in the right
The phase difference between Poes and Pcv during the occlusion tests was close to zero in the five subjects studied in the seated and supine positions (Nos 6–10).

Discussion

In the present study we have assessed the validity of the central venous catheter and the water-filled oesophageal catheter as a measure of pleural surface pressure variations in young adults in different body positions. We have used the occlusion test which requires no active co-operation from the subjects and does not produce any problems because of closure of the glottis [2, 3, 7, 15].

The approach using Poes for measuring indirectly the pleural surface swings is well accepted; on the other hand, the approach using Pcv for this purpose has rarely been studied and has given conflicting results.

Walling and Savage found Pcv to be more accurate and reliable than Poes for estimations of transpulmonary pressure changes in the supine position [17]. However, they compared values of Pcv and Poes obtained with dissimilar systems. The oesophageal catheter was air-filled, while the central venous catheter was liquid-filled with different lengths and diameters, so that the frequency response characteristics or their systems were different and could distort the pressure signals. On the other hand, Hylkema et al. [8] found no significant correlation between $\Delta$Poes and $\Delta$Pcv. These authors also used different catheter-manometer systems. By using three identical systems with adequate frequency-response characteristics, we were able to avoid this kind of error.

Liquid-filled oesophageal catheters are not currently used for measurements in adults because of the greater cardiac artefact in comparison with the oesophageal balloon-catheter system [13]. Another disadvantage of the liquid-filled catheter is the problem of the movements of the catheter, up and down with breathing, at least in the sitting position. Indeed, the gradient of the hydrostatic pressure between catheter tip and pressure transducer could be modified by the respiratory movements and this might generate an error in the measurement of transpulmonary pressure changes. In the supine position, this error would not be significant. Moreover, the occlusion tests do not demonstrate this artefact, due to the absence of real respiratory movements during this test. However, this technique gives a valid measurement of pleural pressure change ($\Delta$Ppl) in healthy newborns [1]. This method is also less unpleasant in adults and in newborns and does not involve the potential errors inherent in the oesophageal balloon-catheter system [3].

Individual values of $\Delta$Pcv/$\Delta$Pm obtained with the occlusion test in the sitting and left lateral decubitus positions were often close to unity (table I). Theoretically [1, 2] the $\Delta$Pcv/Pm or $\Delta$Poes/$\Delta$Pm ratio should be slightly greater than one (about 1.02) because of

<table>
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<tr>
<th>Table III. - The $\Delta$Poes/$\Delta$Pcv ratios during the &quot;occlusion test&quot; in ten subjects</th>
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<tr>
<td><strong>Subject</strong></td>
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<td><strong>Mean</strong></td>
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<td><strong>± SD</strong></td>
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*Each value is the mean of ten measurements. —: not measured.

<table>
<thead>
<tr>
<th>Table IV. - Changes in Pcv due to cardiac artefact in four body positions (% of corresponding $\Delta$Pm)*</th>
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<tbody>
<tr>
<td><strong>Subjects</strong></td>
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<td>10</td>
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<tr>
<td><strong>Mean</strong></td>
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<td><strong>± SD</strong></td>
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</table>

*Each value is the mean of at least three measurements. —: not measured.
decompression of alveolar gas and corresponding lung volume change during the occlusion test. On the other hand, in the supine and right lateral decubitus positions ΔPcv/ΔPm was considerably less than one in three and one subjects, respectively.

In general, we did not find any significant phase lag between ΔPcv and ΔPm during the occlusion test when the ratios were close to unity.

The amplitude and the phase differences observed in some instances were probably due to cardiac artefacts which tended to increase in the supine and right lateral positions (table III). However, a poor transmission of the pleural pressure changes into the superior vena cava is also possible. Indeed, we have often observed this phenomenon in patients with right heart failure; the aberrant ΔPcv/ΔPm ratios seemed to be due to a reduction of the compliance of the vena cava (personal observation).

Individual values of ΔPoes/ΔPm obtained with the occlusion test were close to unity in all body positions except for two subjects in the supine position (table II). Consistent with this, we did not find any appreciable phase lag between ΔPoes and ΔPm during the occlusion test. The group average ΔPoes/ΔPm is generally slightly greater than one and this is in agreement with ASHER et al. [1]. This is probably due to compression of alveolar gas. It is interesting to note that, during spontaneous respiration, ΔPcv was sometimes smaller than ΔPoes in spite of a ΔPcv/ΔPm and ΔPoes/ΔPm ratio close to one in the occlusion test. This may be explained by a vertical gradient in changes of pleural surface pressure, with the greater values towards the lung base and in agreement with IRVIN et al. who, during natural breathing, found pressure swings in the lower oesophagus 30% larger than those in the upper oesophagus [9].

In conclusion, we have shown that in healthy adults the central venous catheter methods and the water-filled oesophageal catheter methods provide, in general, accurate measurements of the change in Ppl, if these methods have been validated by the occlusion test. According to BEARDSMORE et al. [3], measurements of lung mechanics should not be accepted unless ΔPoes/ΔPm or ΔPcv/ΔPm are in excess of 94%. If the ratio is less than 94%, the catheter positions should be adjusted to increase it and/or to reduce the cardiac artefact. By contrast, if the ratio exceeds 103%, a careful check should be made to eliminate any leak in the occlusion system, resulting in an underestimation of Pm.

The central venous catheter system is a valid method for measurement of pleural pressure changes, after a satisfactory occlusion test in healthy adults. It may prove to be a useful tool for the study of lung and chest wall mechanics in critically ill patients with acute respiratory failure, because such patients generally have a central venous pressure catheter in position. Great care must be taken to avoid the use of catheters with too small an internal diameter because their frequency response characteristics could be inadequate.

In the same way, we have validated the oesophageal water-filled catheter method in healthy adults, which is not only accurate but is also more comfortable for patients than the balloon-catheter method.

Appendix

Measurement of the catheter-transducer system response

In conclusion, we have shown that in healthy adults the central venous catheter system is a valid method for measurement of pleural pressure changes, after a satisfactory occlusion test in healthy adults. It may prove to be a useful tool for the study of lung and chest wall mechanics in critically ill patients with acute respiratory failure, because such patients generally have a central venous pressure catheter in position. Great care must be taken to avoid the use of catheters with too small an internal diameter because their frequency response characteristics could be inadequate.

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Individual values of ΔPoes/ΔPm obtained with the occlusion test were close to unity in all body positions except for two subjects in the supine position (table II). Consistent with this, we did not find any appreciable phase lag between ΔPoes and ΔPm during the occlusion test. The group average ΔPoes/ΔPm is generally slightly greater than one and this is in agreement with ASHER et al. [1]. This is probably due to compression of alveolar gas. It is interesting to note that, during spontaneous respiration, ΔPcv was sometimes smaller than ΔPoes in spite of a ΔPcv/ΔPm and ΔPoes/ΔPm ratio close to one in the occlusion test. This may be explained by a vertical gradient in changes of pleural surface pressure, with the greater values towards the lung base and in agreement with IRVIN et al. who, during natural breathing, found pressure swings in the lower oesophagus 30% larger than those in the upper oesophagus [9].

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In the same way, we have validated the oesophageal water-filled catheter method in healthy adults, which is not only accurate but is also more comfortable for patients than the balloon-catheter method.

Appendix

Measurement of the catheter-transducer system response

Errors in measurement of dynamic pressure can have serious consequences in many clinical situations, and consequently the testing and matching of catheter-transducer systems are essential to ensure that the signals recorded are a true reflection of the pressure change measured.

The natural frequency of the Bentley transducers is more than 500 Hz. The catheter has an internal diameter of 1.5 mm and a length of 75 cm. The internal volume of the Bentley Transtec transducer is 0.32 cm³ and that of the catheter is 1.32 cm³. The response characteristics of a catheter-transducer system can be determined by two methods: the transient step or the sinusoidal frequency response [18].

Transient step response

The basis of this method is to apply a sudden step input and record the resultant damped oscillations of the system.

The catheter was sealed at the bottom of a water-filled tube. To check the quality of the square wave, a second shorter transducer-catheter system (8 cm) was also sealed at the bottom of the tube, just beside the first catheter. Both catheters were water-filled. A rubber membrane (a surgical glove) was fitted over the tube and punctured with a burning match. The signals were visualized on a Tektronix storage oscilloscope and photographs taken, using a Tektronix polaroid camera.

The response of the short catheter allowed us to ascertain that the input pressure was not a perfect square wave. Thus, it was not possible to measure the frequency response of the system in terms of 10–90% response time. However, it was possible to measure the amplitude ratio of successive positive peaks and to determine the damping ratio at 0.2–0.3.

Sinusoidal frequency response

The difference with the precedent equipment is in the use of a sinusoidal pressure generator system. The short catheter-transducer system was also connected to the test chamber and the input pressure monitored. The ratio of the amplitude and the phase differences of the output of the two catheter-transducer systems were measured by a transfer function analyser (Solartron-Schlumberger). Different frequencies were tested. We were able to calculate the natural frequency of the system, knowing the damping ratio and using a second-order model. The natural frequency of the catheter-transducer system was estimated at about
200 Hz. Such a high natural frequency with a
dampening ratio of 0.2–0.3 guarantees an adequate
reproduction of the wave forms, as the frequency at
which a fall of 3 decibels (3dB) (about 30% of the
input signal) is observed, far exceeds 10 Hz in our
case [6].

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M. Piret for secretarial assistance and J.P. Peeters for
the illustrations.

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RÉSUMÉ: La validité des techniques du catheter veineux central et
du catheter oesophagien rempli d'eau pour la mesure des variations
de pression pleurale a été évaluée chez dix sujets sans dans
différentes positions corporelles au cours d’efforts inspiratoires à
voies aériennes fermées, en comparant les variations simultanées de
pression buccale (APm) considérées représenter les changements de
pression pleurale, de pression veineuse centrale (APCV) et de
pression oesophagienne (AOE). Les rapports APOC/APM ne
sont proches de l'unité que dans des positions assise et en decubitus latéral gauche,
mais des différences significatives sont parfois observées en
décubitus dorsal et latéral droit. Les rapports APOC/APM ne
s'écarteront qu'exceptionnellement de l'unité, quelle que soit la
position. Lorsque le rapport d'amplitudes est proche de 1, il n'y a
pas de différence de phase appreciable entre APM/APOC et
APM/APC. Nous concluons que les variations de pression pleurale
peuvent dans la plupart des cas être mesurées par les techniques du
catheter veineux central ou du catheter oesophagien rempli de
liquide, si l'on en juge par le test d'occlusion.