# Equipment

# Measurement of pleural pressure with oesophageal catheter-tip micromanometer in anaesthetized humans

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*In spontaneously breathing anaesthetized subjects, we studied a new technique for the measurement of changes in pleural pressure. Seven ASA physical status I patients undergoing general anaesthesia (enflurane 1–2 MAC, nitrous oxide 50%, and oxygen) for minor orthopaedic surgery were studied in the supine position. Changes in oesophageal pressure (ΔPes) were measured by means of a catheter-tip pressure transducer. This micromanometer was positioned according to an occlusion test where ΔPes were compared with the changes in airway opening pressure (ΔPao). Optimizing the signal/noise ratio, we observed a linear relationship between ΔPes and ΔPao. In each patient, the ΔPes/ΔPao relationship was highly reproducible. Using the linear regression analysis to characterize the ΔPes/ΔPao relationship, we have developed a different approach for the positioning of oesophageal catheter. After statistical analysis of the observed ΔPes/ΔPao relationship, a "calibration" factor can be used in order to correct the observed slope of the ΔPes/ΔPao relationship to its theoretical value. We conclude that an oesophageal catheter-tip micromanometer can be used in anaesthetized supine patients to measure changes in pleural pressure.*

*Chez des volontaires anesthésiés et respirant spontanément, nous avons étudié une nouvelle technique de mesure des variations de pression pleurale. Sept patients normaux (ASA I) devant subir une chirurgie orthopédique mineure sous anesthésie générale (enflurane 1–2 MAC, protoxyde d'azote 50%, et oxygène) ont été étudiés en décubitus dorsal. Les variations de pression œsophagienne (ΔPes) étaient mesurées au moyen d'un microcapteur de pression situé à l'extrémité d'un cathéter. Ce micromanomètre était positionné selon un test d'occlusion où les ΔPes sont comparés aux variations de pression à l'ouverture des voies aériennes (ΔPao). En optimalisant le rapport signal/bruit, nous avons observé une relation linéaire entre les ΔPes et les ΔPao. Chez chacun de nos patients, la relation ΔPes/ΔPao était hautement reproductible. Utilisant l'analyse de régression linéaire pour caractériser la relation ΔPes/ΔPao, nous avons développé une approche différente pour le positionnement d'un cathéter œsophagien. Après analyse statistique de la relation ΔPes/ΔPao observée, un facteur de "calibration" peut être utilisé pour corriger la pente observée de la relation ΔPes/ΔPao à sa valeur théorique. Nous concluons donc qu'un micromanomètre œsophagien peut être utilisé pour mesurer les variations de pression pleurale chez les patients anesthésiés et placés en décubitus dorsal.*

**Key words**
LUNG: pleural pressure;
MEASUREMENT TECHNIQUES: occlusion pressure, pleural pressure;
EQUIPMENT: catheter-tip pressure transducer;
POSITION: supine.

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During spontaneous breathing or conventional mechanical ventilation, indirect estimation of changes in pleural pressure (ΔPpl) is often made by measuring the changes in oesophageal pressure (ΔPes). The classical technique used to validate the measurement of ΔPes as a reflection of ΔPpl requires that the subjects perform voluntary static Valsalva and Mueller manoeuvres while keeping the glottis open.[1] The position of the oesophageal catheter is considered acceptable when there is a good agreement between ΔPes and the changes in airway opening pressure (ΔPao). However, in anaesthetized subjects, we must rely on a different approach.

Since 1978, several authors[2–5] have compared ΔPes and ΔPao during spontaneous inspiratory efforts against a closed airway in awake subjects. In 1983, using this dynamic occlusion test and the standard oesophageal balloon technique in anaesthetized supine subjects, Higgs *et al.*[6] demonstrated that ΔPes can reliably reflect ΔPpl when the oesophageal balloon is properly positioned. This approach is adequate for studies in spontaneously breathing subjects and during conventional mechanical ventilation.

For the study of respiratory mechanics at high frequencies (up to 50 Hz), the use of the standard oesophageal balloon technique would not be possible as the frequency response of the oesophageal balloon is inadequate (≈5 Hz). In anaesthetized supine rabbits, Chartrand *et al.*[7] demonstrated that an oesophageal catheter-tip pressure transducer can give adequate estimation of ΔPpl up to at least 50 Hz. In the present study, we wanted to assess the validity of the ΔPes measurement in anaesthetized supine humans when an oesophageal catheter-tip micromanometer was used.

## Methods

Seven ASA physical status I subjects undergoing general anaesthesia for elective orthopaedic surgery on the lower limbs were studied. Their average age (±SD) was 36.3 ± 16.0 yr. The research protocol was approved by the hospital Ethics Committee, and informed consent was obtained from all subjects. An anaesthetist, not directly involved in the experimental protocol, administered the anaesthesia according to the needs of the patient and he was free to interrupt the protocol at any time.

In all subjects, anaesthesia was induced with thiopentone (4–5 $mg \cdot kg^{-1}$) and muscle relaxation was obtained with succinylcholine (1 $mg \cdot kg^{-1}$). Tracheal intubation (Sheridan/HVT tracheal tube, 8.0 mm ID) was performed after laryngeal topical anaesthesia with lidocaine (≈1 $mg \cdot kg^{-1}$). Anaesthesia was maintained with enflurane (1.5–3.0%) in a mixture of 50% nitrous oxide and oxygen. After stabilization of the anaesthesia, the patients were maintained breathing spontaneously and in the supine position.

A 5-F catheter-tip pressure transducer (Millar SPC-350) was inserted through a nostril and passed into the stomach. It was then slowly withdrawn to the oesophagus; this was indicated by the negative pressure swings during inspiration. Compared with the oesophageal balloon technique, the catheter-tip micromanometer has a very small volume-pressure displacement coefficient (<0.001 $\mu l \cdot kPa^{-1}$) and large cardiac artifacts can be observed in the retrocardiac portion of the oesophagus (1–3 kPa). However, pulling the catheter more proximally, one can observe a sudden decrease in the amplitude of these cardiac artifacts. We used this position in all our subjects because the signal/noise ratio was greatly improved and a more proximal position was found to decrease the signal/noise ratio. The signal/noise ratio was obtained by dividing the amplitude of the ΔPes related to the respiratory efforts (signal) by the amplitude of the cardiac artifacts (noise). At end-expiratory volume, the tracheal tube was then occluded manually by snugly inserting into its lumen a piezoresistive pressure transducer (Micro Switch 143PC03D). The Millar transducer measured ΔPes and the Micro Switch transducer, ΔPao. During the next three to four spontaneous breathing efforts, the ΔPes were displayed as a function of the ΔPao on a digital storage oscilloscope (Gould 1604). During this dynamic occlusion test, two criteria were used to assess the proper positioning of the oesophageal micromanometer: (1) the cardiac artifacts had to be small (≈0.2 kPa); (2) the ΔPes/ΔPao relationship had to be linear and without hysteresis. The position of the catheter being ascertained, three periods of data acquisition (*vide infra*) were performed within a ten-minute period.

### *Data acquisition*

As the experimental set-up was designed for studies of respiratory mechanics at high frequencies, the frequency response of each component was verified. The frequency response of both pressure transducers had been tested using a loudspeaker driven by a sinewave generator and also using step impulses. The oesophageal catheter-tip pressure transducer and the Pao transducer had a flat frequency response over 250 and 4,000 Hz, respectively. Their output signals were amplified (Hewlett Packard, medium gain amplifier 8802A), displayed on a storage oscilloscope (*vide supra*), and low-pass filtered (Frequency Devices 902LPF) with a cut-off frequency set at 300 Hz. The data acquisition was performed in real time on an "AT compatible" computer with an A/D converter (Data Translation DT2801A) sampling at 1,024 Hz. For each signal channel, a total of 8,192 data points was sampled in each period of data acquisition. The frequency response of the entire measuring system was verified using step impulses. The two signals had an identical behaviour in both amplitude and phase up to over 200 Hz.

### *Data analysis*

For each period of data acquisition, the slope of the ΔPes/ΔPao relationship was determined by linear regression. In order to characterize the ΔPes/ΔPao relationship observed in each subject, the mean slope and its standard deviation, the coefficient of determination, and the percentage of reproducibility of the mean slope were computed. The percentage of reproducibility of the mean slope was calculated as: 100% − S.E.M.% (S.E.M.% being the

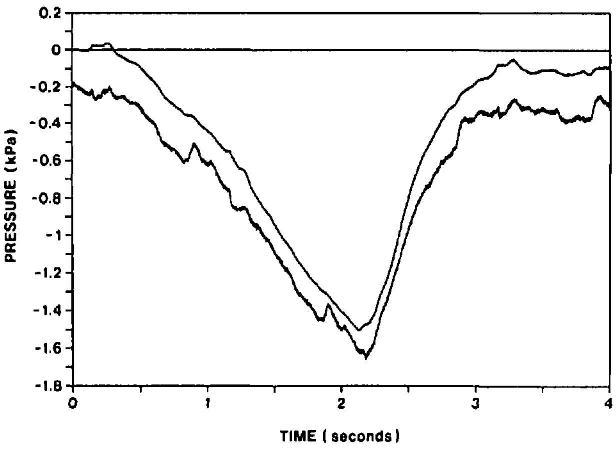


FIGURE 1 Changes of airway opening pressure (upper tracing) and oesophageal pressure (lower tracing) observed during one spontaneous inspiratory effort performed against an occluded tracheal tube in one patient.

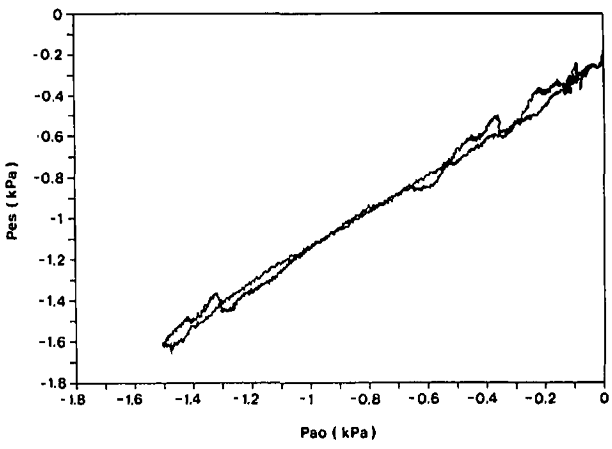


FIGURE 2 ΔPes/ΔPao relationship for the occluded inspiratory effort shown in Figure 1. In this patient (#4), the amplitude of the cardiac artifacts is ≈0.1 kPa.

standard error of the mean slope expressed as a percentage of that mean value). In order to differentiate respiratory and cardiac components, fast Fourier transforms (FFT) were performed on each signal.

## Results

With the oesophageal micromanometer positioned at the level where the cardiac artifacts decreased suddenly, a linear ΔPes/ΔPao relationship was observed in all subjects. The distance between the oesophageal micromanometer and the nostril ranged between 28 to 38 cm and no correlation was found with the height of the patients.

Figure 1 shows the changes in Pao and Pes during a typical occlusion test. Small cardiac artifacts can be observed in the Pes signal (lower tracing). The relationship between ΔPes and ΔPao during the same occluded inspiratory effort is shown in Figure 2. The mean slope of the ΔPes/ΔPao relationship observed in each patient (Table) ranged from 0.69 to 1.02. However, in each individual, the percentage of reproducibility of the mean slope ranged from 97.0 to 99.9%. Furthermore, the variance accounted for by the individual regression lines ($r^2$) ranged from 92 to 100% and the average variance not accounted for by the linear regression model was only ≈3%. The analysis of the FFT data indicates that the cardiac artifacts were the major contributors to this residual variability.

## Discussion

In previous studies,[2-7] the measurement of the ΔPes was considered to reflect the ΔPpl adequately if the dynamic occlusion test produced a ΔPes/ΔPao relationship with a slope close to 1. This simple technique is the conventional method of positioning an oesophageal balloon. However, in the presence of large cardiac artifacts and if the ΔPes/ΔPao relationship is linear and highly reproducible, the most important criterion should be the optimization of the signal/noise ratio. Visualizing the Pes signal while positioning an oesophageal micromanometer (or balloon), one can usually find the quasi-optimal signal/noise ratio. The optimal signal/noise ratio being used to improve the "purity" of the Pes signal, the scattering of the ΔPes/ΔPao relationship is minimal and, using linear regression analysis, the highest coefficient of correlation will be obtained. In this study, we observed linear ΔPes/ΔPao relationships in all the patients and, for each subject, this relationship always had a percentage of reproducibility over 97%. Thus, we focused on improving the signal/noise ratio.

Using the standard oesophageal balloon technique in anaesthetized supine subjects, Higgs *et al.*[6] observed that the mean amplitude of the cardiac artifacts was relatively constant (≈0.2–0.3 kPa) at different levels in the oesophagus. However, they mentioned in their discussion: "In

TABLE ΔPes/ΔPao relationships observed in seven patients

| *Subject #* | *Mean slope ± SD** | *% of reproducibility* | $r^{2\dagger}$ |
|---|---|---|---|
| 1 | 0.958 ± 0.004 | 99.7% | 0.9859 |
| 2 | 0.982 ± 0.015 | 99.1% | 0.9690 |
| 3 | 0.923 ± 0.007 | 99.5% | 0.9456 |
| 4 | 0.917 ± 0.002 | 99.9% | 0.9959 |
| 5 | 1.024 ± 0.022 | 98.8% | 0.9716 |
| 6 | 0.691 ± 0.022 | 98.2% | 0.9721 |
| 7 | 0.758 ± 0.039 | 97.0% | 0.9464 |

*SD = standard deviation.
†$r^2$ = coefficient of determination.

our subjects, the optimum balloon positions did not always correspond to the locus of minimum cardiac artifact. The same was true for the conventional balloon position (10 cm from the cardia). Indeed, in the latter position, the cardiac artifact ranged between 4 and 7 cm $H_2O$ (0.4 and 0.7 kPa) in three individuals. In all these subjects, however, by repositioning the balloon, a smaller cardiac artifact could be obtained while maintaining an accceptable ΔPes/ΔPt ratio." Using an oesophageal micromanometer with a very small volume-pressure displacement coefficient, we observed large cardiac artifacts (1–3 kPa) in the retrocardiac portion of the oesophagus. But, pulling the catheter more proximally, we observed a sudden decrease in the amplitude of these artifacts which became similar to those observed by Higgs *et al.* This reduction of the noise level improved greatly the signal/noise ratio. However, in two subjects (#6 and #7), the observed ΔPes/ΔPao ratio would not be acceptable according to the conventional method of positioning oesophageal catheters.

Studying the ΔPes/ΔPao relationships at different levels in the oesophagus, Higgs *et al.*[6] observed that, in each subject, the optimal slope (close to 1) could be found at 5 to 15 cm from the cardia. Using this conventional method, most investigators will perform an adequate positioning of the oesophageal balloon. Using computerized data acquisition and linear regression analysis, we used a different criterion to select the optimal position of our oesophageal micromanometer: the position where the highest signal/noise ratio and coefficient of correlation can be observed. If, due to thoracic gas decompression during occluded inspiratory efforts, the theoretical ΔPes/ΔPao ratio is known to be $\approx 1.02$, it is then possible to correct the slope of the observed ΔPes/ΔPao relationship if it is highly reproducible. Dividing the theoretical ΔPes/ΔPao ratio by the mean slope of the observed ΔPes/ΔPao relationships, we obtained a "calibration factor" which could be used to correct the observed ΔPes. With our approach, the corrected ΔPes are not only an "acceptable" (± 10%) estimation of the ΔPpl but they are the closest estimation possible (± S.E.M.%) within the physiological and statistical limits.

As spontaneous breathing is a low-frequency phenomenon, the FFT analyses performed on the Pes and Pao signals did not show harmonics of the respiratory component of the signal over 5 Hz. If the frequency content of the respiratory component of the signal is under 5 Hz, the standard oesophageal balloon technique remains an adequate and inexpensive approach to the measurement of the ΔPes. However, the study of respiratory mechanics by high-frequency forced oscillations requires measurement techniques having a much better frequency response. Comparing the FFT analyses performed on simultaneous Pes and Pao signals, we were able to identify that the frequency content of the cardiac component of the signal was the most important noise in the Pes signal.

We conclude that, in anaesthetized subjects breathing spontaneously in the supine position, the ΔPpl can be estimated from the ΔPes measured with an oesophageal micromanometer. However, as the conventional method of positioning oesophageal catheter can not be used in all subjects, we have developed a different approach using the linear regression analysis to characterize the observed ΔPes/ΔPao ratio and correcting this ratio to its theoretical value subsequently.

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