

LUNG WATER ESTIMATION USING AN EXTERNAL SENSING CATHETER

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INVESTIGATION OF PATIENTS often fails to detect subclinical oedema until hypoxia and respiratory acidosis have occurred. Early detection of pulmonary oedema would hasten and improve therapy, possibly preventing these complications and obviating the need for artificial ventilation.

Radiologists have used radiographs to detect pulmonary oedema but quantitation, although potentially possible, is subject to great uncertainty.¹ To differentiate between pulmonary oedema and pulmonary congestion by radiography requires ideal conditions, an unlikely occurrence in an Intensive Care Unit (ICU).²

Other investigators have quantitated pulmonary extravascular water volume (PEWV) using double indicator dilution techniques. Chinard³ first demonstrated this technique using tritiated water as the diffusible indicator and T-1824 Evan's Blue as the intravascular indicator. Other intravascular indicators have been used: indocyanine green dye, chromium tagged red cells and albumin¹³¹I.⁴⁻⁶ These indicators have several disadvantages. These include the difficulties of handling radio-active materials, the need for costly analysis equipment, blood loss of about 50 ml per determination and limited repeatability due to radiation build-up. However, the major disadvantage is that the tritiated water technique only detects 60 per cent to 70 per cent of the water that can be found using a post-mortem weighing technique.⁷

To overcome these problems, investigators have searched for new indicators. Pearce and Beazell⁸ suggested the use of heat as a diffusible indicator. Noble and Severinghaus⁷ used 3 per cent sodium chloride at room temperature. In this case heat acts as a non-molecular diffusible indicator and the sodium ions remain within the vessel to produce a change in blood electrical conductivity. This technique measures cardiac output (\dot{Q}) and the extravascular thermal volume of the lung (ETV_L), a value that has correlated well with post-mortem measurements of PEWV.^{7,9} We used a special sensing catheter with transducers at the distal end but within the lumen of the catheter to detect blood conductivity and temperature changes. The catheter was inserted through the femoral artery until it was just distal to the aortic valve. Blood withdrawal is necessary to record the temperature and conductivity dilution curves. Anderson¹⁰ and Dunegan¹¹ have used the ETV_L technique in dogs and described a sensing catheter that required no blood withdrawal.

We found the ETV_L technique to be accurate in following the time course of

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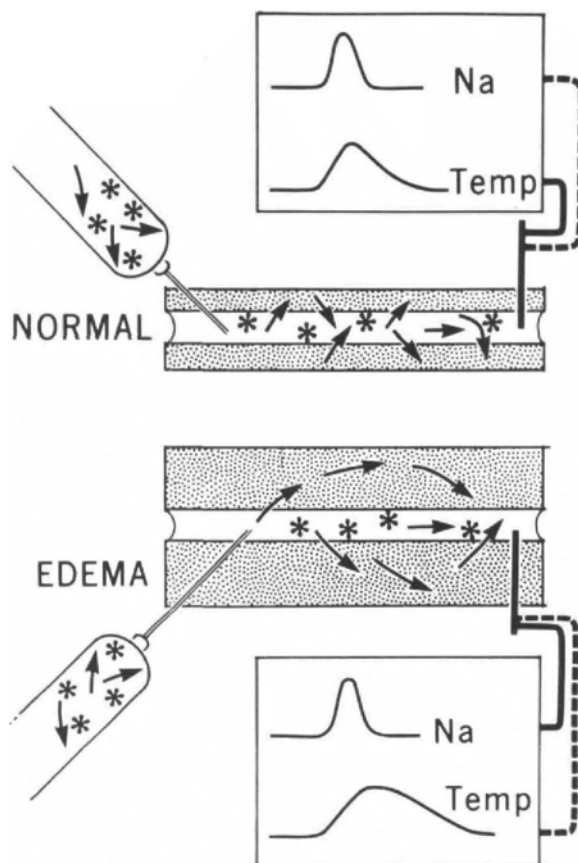


FIGURE 1. Principles of the ETV_L method. Schematic drawing of normal and oedematous states. Three per cent sodium chloride is injected by a syringe into the pulmonary artery and detection of calories (\uparrow) and sodium ions (\circ) is made in the aorta. Note the temperature curve is prolonged in the oedematous state.

pulmonary oedema in a number of dog studies^{2,7,9,12} and in view of this we decided to use the technique in human patients. To emulate our dog technique in patients a catheter was manufactured commercially, but because of its relatively large size it proved troublesome to pass along the aorta. The conductivity electrodes also reduce the internal diameter so that blood withdrawal and flushing are difficult. We constructed an external sensing catheter that will attach to the hub of any standard arterial catheter. This eliminates the insertion of the sensing catheter into the artery and allows blood withdrawal and flushing.

This technique offers the advantages of monitoring \dot{Q} as well as ETV_L , virtually unlimited repeatability, relatively uncomplicated instrumentation, and no blood loss. It has the potential for revealing sub-clinical oedema, differentiating between congestion and pulmonary oedema, and determining the efficacy of various types of therapy.

The experiments reported here were done to evaluate the accuracy and reliability of the external catheter in monitoring ETV_L and \dot{Q} by comparison with the internal

sensing catheter. Comparisons were made in normal dogs and in dogs with gross pulmonary oedema.

PRINCIPLE OF THE METHOD

Figure 1 illustrates the principle of the method. In practice the injection site is the pulmonary artery and the detection site a point distal to the aortic valve. When 3 per cent sodium chloride at room temperature is injected, calories, which are non-molecular and not bound to any of the blood components, cross the vessel wall and move into the extravascular tissues and fluid. This temperature change is reversible and the path of the extravascular indicator will depend mainly on the quantity of fluid around the vessel. In oedema, because of the larger volume of distribution, the calories have a longer pathway compared to the normal vessel, resulting in a skewed thermal curve with a longer mean transit time. The sodium ions, however, remain within the vessel and their transit time will be unaffected by the oedema. Therefore, the difference in transit time (Δt) between calories and sodium ions will be longer in the vessel surrounded by water.

Calculation of Thermodilution Cardiac Output:

Cardiac output is calculated using the formula

$$\dot{Q}_T = \frac{(V_T - V_I)D_I S_I \Delta T_I}{D_B S_B \int_0^\infty T_B t_B dt}$$

Where:

\dot{Q}_T = Cardiac Output

V_T = total volume delivered from the injection syringe determined by weighing

V_I = volume of injectate in the portion of catheter inside the dog.

D_I = density of injectate

S_I = specific heat of injectate

ΔT_I = change of temperature between blood and injectate

D_B = density of blood

S_B = specific heat of blood

$\int_0^\infty T_B t_B dt$ = area under the temperature time curve in °C seconds.

The area under the temperature curve is determined by planimetry using a half area method described by Yousof.¹³

CALCULATION OF ETV_L

The product of the thermal dilution cardiac output (\dot{Q}_T) and the mean transit time for calories to pass through the lungs gives the thermal volume (Figure 2). The product of \dot{Q}_T and the mean transit time for the sodium ions gives the intravascular volume. Subtraction of the intravascular volume from the thermal volume gives the extravascular thermal volume (ETV_T). In practice this simplifies to multiplying the difference in mean transit times between calories and sodium ions by the \dot{Q}_T .

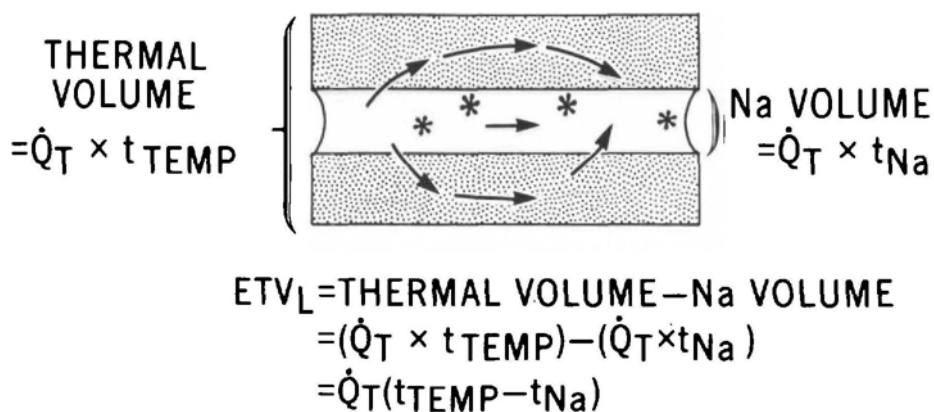


FIGURE 2. Calculation of ETV_L .
 The extravascular indicator is calories (\uparrow) and the intravascular indicator is sodium ions (\circ).
 \dot{Q}_T = cardiac output. $T_{t_{\text{TEMP}}}$ = Mean transit time for calories. $T_{t_{\text{Na}}}$ = Mean transit time for sodium ions.

METHODS

Mongrel dogs weighing 12 to 25 kg were anaesthetized with pentobarbitone 30 mg/kg. They were intubated and allowed to breathe spontaneously while lying supine. The experimental arrangement is shown diagrammatically in Figure 3. Using pressure monitoring, a flexible silastic injection catheter containing a thermistor (Veco)* near its tip was placed in the pulmonary artery through the external juglar vein.

An internal sensing catheter with conductivity electrodes and a thermistor near its tip⁷ was placed just distal to the aortic valve through the left femoral artery.

A catheter was inserted into the right femoral artery so that the hub of the catheter was in direct contact with the skin. Initially we used a short 20 cm thin-walled catheter. Later, in an attempt to improve our results, we used a long 55 cm thick walled catheter, Dynetech 5.5 Fr. Polyethylene. An external sensing catheter (Figure 4) similar in construction to the internal catheter but with a connector at the tip and the thermistor extended 10 cm was attached to the right femoral artery catheter, insulated and strapped to the dog's leg to minimize temperature changes. The extension of the thermistor beyond the connector ensured that the thermistor was inside the femoral artery catheter and just inside the body. This produced a more stable baseline.

For determination of \dot{Q} and ETV_T , 5 ml of 3 per cent sodium chloride was injected rapidly into the pulmonary artery while recording injectate temperature. Blood was withdrawn alternately from the external or internal sensing catheters at a constant rate, so that temperature and conductivity time curves were recorded on a Hewlett Packard 7100 BM recorder. After each determination, blood was re-infused through the femoral vein.

After control measurements were taken, warmed 10 per cent dextran 40 in normal saline was infused to produce an increase in ETV_L leading to pulmonary oedema.

*Victory Engineering Corp. Springfield, New Jersey.

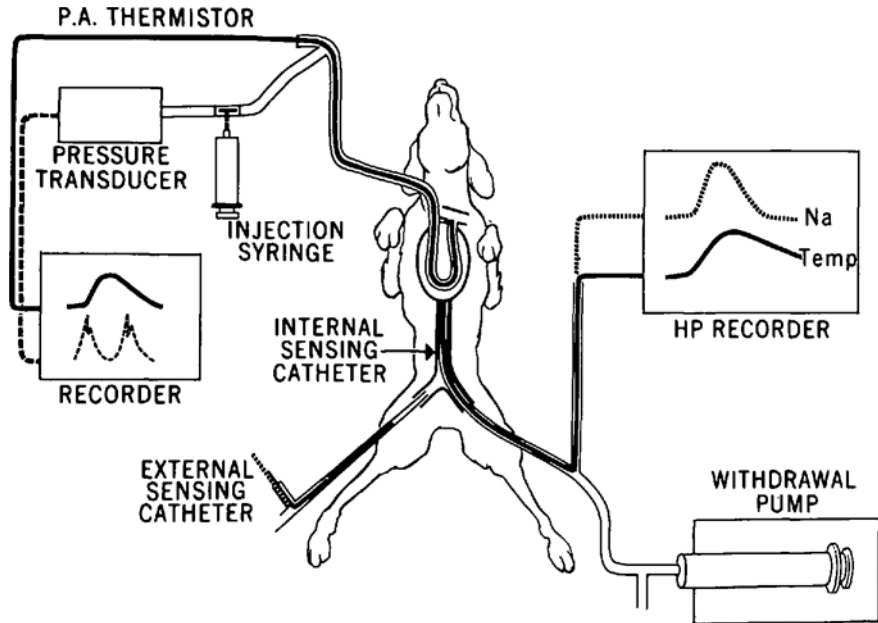


FIGURE 3. Diagram of The Methods: Indicators are injected into the pulmonary artery and detected by either the internal sensing catheter at a point distal to the aortic valve or the external sensing catheter. The withdrawal pump is shown attached to the internal catheter but in practice a switching arrangement allows withdrawal from either catheter.

The normal range for ETV_L is 5 to 7 ml/kg. Low values were obtained in two dogs by removing blood.

RESULTS

With the external sensing catheter connected to the short thin-walled arterial line, 145 comparisons of \dot{Q} and ETV_L measured with the internal and external catheters were obtained in ten dogs. The correlation co-efficient for \dot{Q} was 0.93, and the mean difference (internal catheter \dot{Q}_T - external catheter \dot{Q}_T) was -0.32 ± 0.05 l/min, a statistically significant difference ($p < 0.001$). The correlation

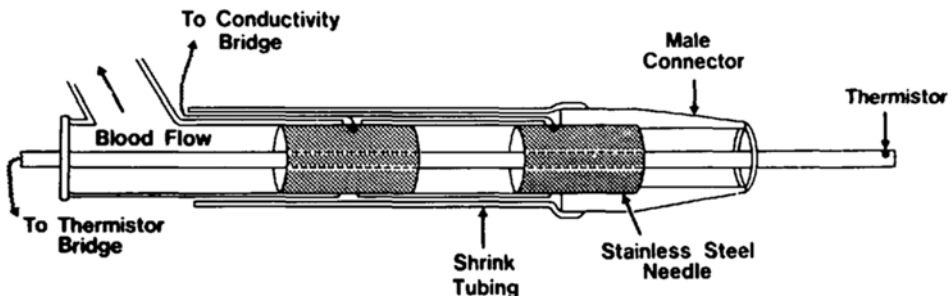


FIGURE 4. External sensing catheter with the thermistor extended 10 cm beyond the tip.

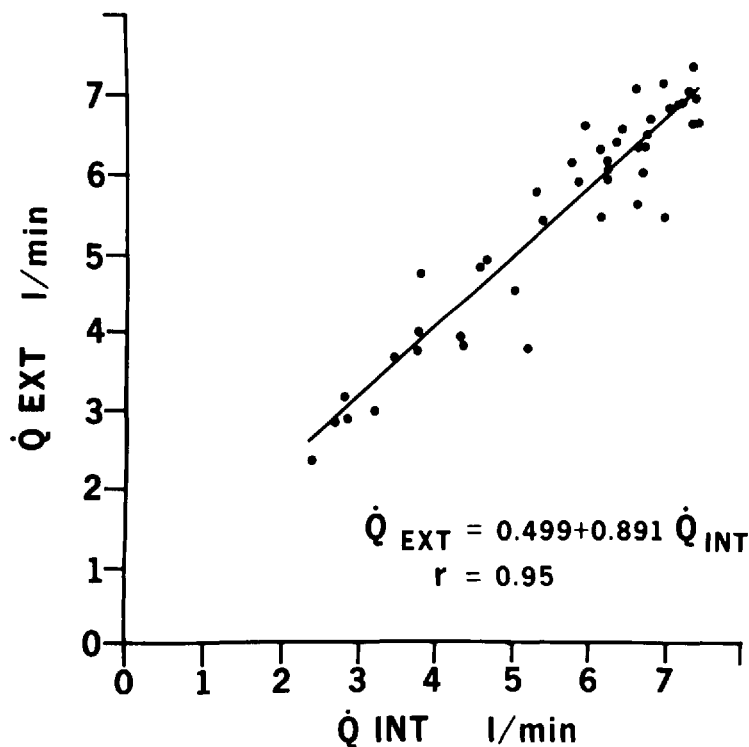


FIGURE 5. A comparison of \dot{Q} measured with the internal sensing catheter (\dot{Q}_{int}) and the external sensing catheter (\dot{Q}_{ext}). The external sensing catheter was connected to a long thick walled arterial line.

coefficient for ETV_L was 0.91 and the mean difference (internal catheter ETV_L - external catheter ETV_L) was -2.77 ± 0.38 ml/kg, a statistically significant difference ($p < 0.001$).

When the external sensing catheter was connected to the long thick-walled arterial line, 45 comparisons of \dot{Q}_T and ETV_L measured with the internal and external catheters were obtained in two dogs. The correlation for \dot{Q}_T was 0.95, (Figure 5) and the mean difference (internal catheter \dot{Q}_T - external catheter \dot{Q}_T) was 0.12 ± 0.07 l/min. This observed difference was not statistically significant ($p > 0.1$). The correlation coefficient for ETV_L was 0.96 (Figure 6) and the mean difference (internal catheter ETV_L - external catheter ETV_L) was -2.46 ± 0.26 ml/kg, a statistically significant difference ($p < 0.001$). The difference of 2.46 ml/kg between internal and external ETV_L values was consistent throughout the range of ETV_L values.

DISCUSSION

Previous dog studies using an internal sensing catheter to detect thermal and conductivity indicators have shown the double indicator dilution technique to be accurate and reliable.^{7,9} This study shows a reasonably good agreement between

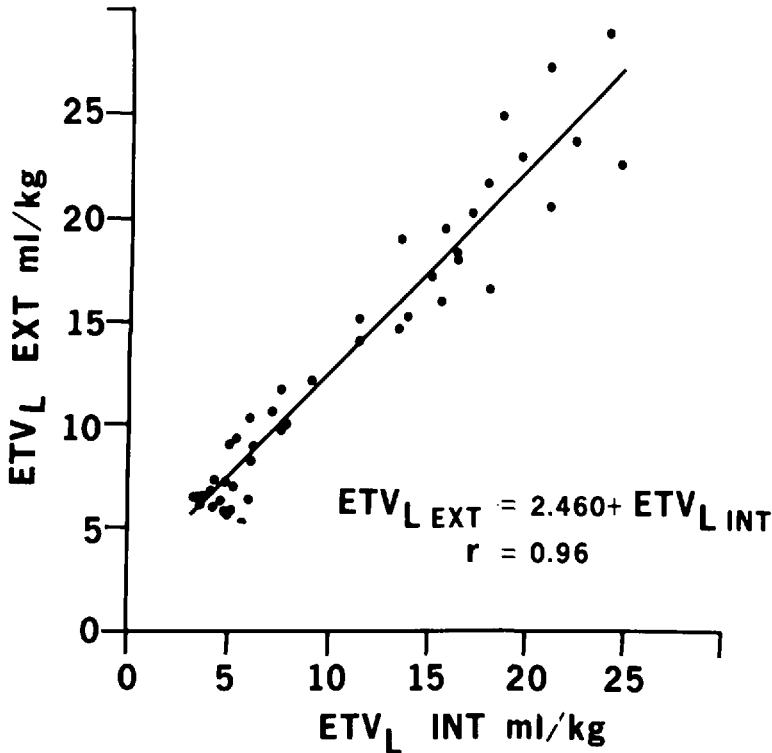


FIGURE 6. A comparison of ETV_L measured with the internal sensing catheter ($ETV_{L\ int}$) and the external sensing catheter ($ETV_{L\ ext}$). The external sensing catheter was connected to a long thick walled arterial line.

the external catheter technique and the internal catheter technique of measuring \dot{Q} and ETV_L , when the external catheter is attached to a 55 cm long thick-walled, femoral arterial line. With the external catheter attached to a short femoral arterial line \dot{Q}_T and ETV_L were overestimated by a statistically significant amount. Using a long thick walled catheter, there was no significant difference between the internal and external determinations of \dot{Q}_T .

Measurement of ETV_L requires the detection of an intravascular indicator, sodium, and an extravascular indicator heat. The extravascular indicator is used to determine \dot{Q}_T , a factor necessary for the calculation of ETV_L . There should be no loss of indicators between the sites of injection and detection. As calories can cross the vessel wall, introducing the possibility of radial heat exchange, the distance between the sites of injection and detection should be as short as possible. Arfors,¹⁴ however, concluded that there was no net loss of heat in the pulmonary circulation, and even at very low cardiac outputs net loss of indicator, does not present an obstacle to the use of the thermodilution method for the estimation of \dot{Q}_T . In dogs a comparison of dye dilution and thermal dilution cardiac outputs with the thermal indicator crossing the lungs (correlation coefficient 0.88), indicated that there was no significant irreversible loss of heat in the pulmonary vascular bed even in pulmonary oedema.¹⁵ These results indicate that injection

into the pulmonary artery and detection in the aorta is satisfactory. In this investigation the higher \dot{Q}_T observed with the short thin walled femoral arterial line may be explained as a result of the system's dimensions, now including the longer pathway to the external catheter, which will tend to increase radial heat exchange resulting in a small loss of indicator and producing too small an area under the thermal dilution curve.

Using the thick-walled catheter we did not observe a significant difference between the internal and external catheter \dot{Q}_T . Theoretically this would indicate no loss of indicator in the system and this could be explained by the fact that the long catheter samples blood just distal to the aortic valve and the thick wall with a low thermal conductivity prevents radiant heat exchange down the aorta.

Measurements of ETV_L require detection of the thermal indicator and an intravascular indicator, sodium. Chinard¹⁶ and Pearce¹⁷ found no evidence of sodium leak across the normal lung endothelium in the first passage. Pearce¹⁷ found a small loss of sodium during one transit in high pressure pulmonary oedema. In a previous study we were not able to detect this loss in pulmonary oedema.⁹ This was also substantiated by comparing ETV_L with post-mortem measurements of pulmonary extravascular tissue weight (PETW). The ratio of ETV_L over PETW in a group of dogs with pulmonary oedema was 1.2 (N = 36).⁷

Using the short catheter the mean ETV_L was overestimated by 2.77 ± 0.38 ml/kg and using the long catheter by 2.46 ± 0.26 ml/kg. These results can be explained in the following way. The calculation of ETV_L depends upon the \dot{Q}_T but using the long catheter we did not observe any statistical difference between the internal and external \dot{Q}_T . This would tend to indicate that there must be distortion of the curves altering the transit times. Using a long catheter would produce laminar flow and distort the dilution curves, producing a diminution in height and a general prolongation of the curve. The area under the curve would be unaffected but the mean transit time would be prolonged, and it is possible that the thermal curve is more distorted than the conductivity due to some reversible heat exchange with the wall of the catheter. These factors would produce a larger difference between the mean transit times for the thermal and conductivity curves, and overestimate ETV_L . However, the correlation coefficient of 0.96 that we have found indicates a close relationship and the potential for use in clinical situations. Ideally, therefore, to measure ETV_L an internal sensing catheter should be used. Up to now, however, there have been no reports in the literature of an internal sensing catheter being used in man. If a commercial catheter is not available, and if clinical or pathological circumstances such as narrowing of vessels due to atherosclerosis prevent the insertion of an internal sensing catheter, ETV_L measured with an external catheter will yield a result that can be related to the internal ETV_L value, and can be used for clinical studies.

This technique allows us to determine ETV_L in patients with long 55 cm thick-walled indwelling femoral arterial lines and the addition of a Swan-Ganz catheter containing a thermistor.

SUMMARY

A method for measuring pulmonary oedema (ETV_L) is described using sodium ions as the intravascular indicator and heat as the extravascular indicator. The

technique offers the advantage of virtually unlimited repeatability, relatively uncomplicated instrumentation and no blood loss. There is also the potential for differentiating between pulmonary oedema and pulmonary congestion and determining the efficacy of therapy.

A sensing catheter to detect blood conductivity and temperature changes is required. Ideally the sensing catheter should be situated at a point just distal to the aortic valve. However, a commercially manufactured detecting catheter we had built proved troublesome to insert because of its relatively large diameter. Therefore, an external sensing catheter has been constructed to measure ETV_L , and the values obtained have been compared with those from an internal catheter. There was no difference between the internal and external catheter \dot{Q}_T , but ETV_L was consistently overestimated by 2.46 ± 0.26 ml/kg. However, this value can be related to the internal value and can be used for clinical studies.

RÉSUMÉ

La mesure de l'eau pulmonaire extra-vasculaire (ETV_L) s'est butée jusqu'ici à des difficultés techniques qui la rendaient à peu près impraticable. En cherchant des indicateurs plus maniables que les isotopes, Pearce et Beazell ont proposé d'utiliser la chaleur qui en l'occurrence se comporte comme un indicateur non moléculaire diffusible. Noble et Severinghaus utilisent une solution de NaCl à 3 pour cent à la température de la pièce: la diffusion thermique sert d'indicateur extra-vasculaire et les ions sodium d'indicateur intra-vasculaire. Ce travail décrit l'emploi de ces indicateurs pour mesurer l' ETV_L . La technique nécessite des instruments relativement simples, n'entraîne pas de perte de sang et est virtuellement répétable à satiété.

Il faut disposer d'un cathéter capteur capable de percevoir des changements de la conductivité du sang et de sa température. De façon idéale, ce capteur se place dans l'aorte, tout près de la valve aortique. Cependant, celui qu'on nous avait fabriqué, s'est avéré impraticable à cause de sa taille et aussi nous en avons conçu un autre pour usage externe. Les mesures de ETV_L et de débit cardiaque par diffusion thermique (Q_T), obtenues par l'un et l'autre cathéter ont été comparées: les Q_T étaient tout à fait comparables d'un cathéter à l'autre mais l' ETV_L était constamment surestimé par le capteur externe. Cependant, l'information recueillie par ce capteur externe peut être redressée et utilisée cliniquement.

ACKNOWLEDGMENTS

We wish to thank Mrs. N. Bell, Mr. G. Carmichael, and Mr. G. Caskanette for their technical assistance, Miss C. Mindorff for help with the manuscript, and the Departments of Medical Art and Medical Photography at St. Michael's Hospital.

We thank Abbott Labs. Ltd. for supplying the Nembutal.

This work was supported by Canadian Thoracic and Respiratory Disease Assoc. Grant number 3-333-269-30.

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