An adequate strategy for the thermodilution technique in patients during mechanical ventilation

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Abstract. The application of the thermodilution method in conditions associated with variations in blood flow implies a misuse of the Stewart Hamilton equation. Therefore, we studied the reliability of the thermodilution method for the estimation of mean cardiac output (CO) during mechanical ventilation in patients (n = 9). Variation of the injection moment in the ventilatory cycle elicited a cyclic variation of CO estimates. This variation was not the same for all patients neither in phase nor in amplitude. Therefore, no specific phase in the ventilatory cycle could be selected for an accurate estimation of mean CO. Averaging CO estimates randomly distributed in the ventilatory cycle led to an improvement of accuracy with the square root of the number of observations. The average of two estimates equally spread in the ventilatory cycle was similar to the variation in the average of four random estimates. We conclude that averaging of 3 or 4 estimates spread equally over the ventilatory cycle is an adequate strategy to estimate mean cardiac output in patients reliably.

Key words: Cardiac output - Mechanical ventilation - Multiple injections - Thermodilution

For an accurate estimation of mean cardiac output using the thermodilution method several conditions have to be fulfilled: (i) no loss of indicator, (ii) complete mixing of indicator and blood, (iii) a constant bloodflow, and (iv) a constant baseline temperature. Under these conditions the Stewart-Hamilton equation, as incorporated in many commercial cardiac output computers, can be used. During mechanical ventilation, when bloodflow is modulated by cyclic changes in intra-thoracic pressure [1, 2], the Stewart-Hamilton equation is misused. In practice this may lead to a considerable scatter in random estimates of cardiac output even when the measurements are performed during otherwise haemodynamically stable conditions. These cardiac output values are dependent on the moment of injection of indicator in the ventilatory cycle, in pigs [3-5], dogs [6, 7], and men [8, 9]. Recommendations for an accurate estimation of mean cardiac output during mechanical ventilation are contradictory. Stevens et al. [9] recommended multiple injections at the end of expiration, whereas Okamoto et al. [8] recommended paired measurements at mid-inspiration and mid-expiration. From our animal studies [3-5] we concluded that mean cardiac output could be estimated accurately by calculating the averaged value of four measurements equally spread over the ventilatory cycle. Schneider and Powner [7] confirmed this conclusion in dogs and in one patient.

The objective of the present clinical study was to evaluate the errors in the thermodilution cardiac output estimates during mechanical ventilation in patients in order to find an adequate strategy for a reliable estimation of mean cardiac output.

Methods

Nine male patients aged 55 to 67 years were studied after coronary artery bypass surgery. All suffered from multiple vessel disease, without previous myocardial infarctions, and all had stable angina pectoris with normal ventricular function. None had acute or chronic pulmonary disease. As premedication, the patients received 5 mg of lorazepam p.o.. Anaesthesia was induced with fentanyl (100 μg/kg IV), administered over 5 minutes and pancuronium bromide (0.1 mg/kg) was given to assure complete muscle relaxation. Additional small doses of fentanyl and pancuronium were used as needed. To control blood pressure after sternotomy and to facilitate rewarming after the extracorporeal circulation, sodium nitroprusside was administered (2-4 μg/kg/min). In none of the cases were cardiac stimulants needed. The patients were ventilated with an oxygen/air mixture at a rate of 8-10 breaths per min and an insufflation/inspiratory pause/expiratory ratio of 25%/20%/55%. The ventilatory volume was adjusted to maintain a P\textsubscript{a}CO\textsubscript{2} between 32 and 42 mmHg. No positive and expiratory pressure was applied.

The instrumentation of the patients was not different from the normal clinical routine. A radial artery cannula and a 7.5 F Swan Ganz catheter were inserted. The Swan Ganz catheter (Edwards 93 A-131) was inserted via the internal jugular vein and special attention was given to the position of the thermistor in the pulmonary artery to avoid an
Measurements and estimation of cardiac output

Electrocardiogram, radial arterial pressure, pulmonary arterial pressure, central venous pressure, tracheal pressure, ventilatory flow, and body temperature were monitored on a chart recorder (Gould ES 1000) to check the stability of the patients during a series of 12 measurements. Patients with a change in one of the pressures of more than 5% over the period of a series were excluded from the study.

Injection of 5 ml glucose solution (5%) at room temperature was automatically performed by a phase controller and a pneumatically driven syringe, after a manual start of the cardiac output computer. The syringe was delivered through the Swan Ganz catheter, within 1 s. After 12 seconds the syringe was automatically refilled. The moment of injection was dependent on a start signal given by the operator and the moment in the ventilatory cycle set on the phase controller. The moment in the ventilatory cycle was derived from the Siemens servo ventilator (900 B). This ventilator delivers 100 impulses during each ventilatory cycle giving a subdivision in percentages. These impulses were used to feed a counter in the phase control unit. The counter was reset at the start of each insufflation.

Experimental protocol

A series of twelve thermodilution measurements was carried out during haemodynamically stable conditions. A cardiac output measurement was repeated if the COM 1 computer showed an alert signal and the tracing of the dilution signal showed an abnormal curve. At least five ventilatory cycles were inserted in between two measurements, so each series was performed in approximately 9–10 minutes. The injections were done successively at the phases 0%, 25%, 50%, 75%, 8%, 33%, 58%, 83%, 17%, 42%, 67%, and 92% of the ventilatory cycle, where phase zero was chosen at the start of insufflation. The mean of all twelve cardiac output estimates was accepted to be the real mean cardiac output. Each measurement was expressed as a percentage of this mean value.

Averaging of estimates

Two types of selection procedures were used: a systematic selection and a random selection of single estimates (Fig. 1), as described in detail before [4] and briefly summarized here.

Systematic selection

A two-point-average was obtained by the average of two points half a ventilatory cycle apart. There were 6 such two-point-averages available from a series of 12 single estimates, i.e., 0% + 50%, 8% + 58%, etc. up to 42% + 92%. Four three-point-averages were calculated similarly, i.e., 0% + 33% + 67%, 8% + 42% + 75%, 17% + 50% + 83%, and 25% + 58% + 92%. The three four-point-averages per series were obtained from the phases 0% + 25% + 50% + 75%, 8% + 33% + 58% + 83%, and 17% + 42% + 67% + 92%, respectively.

Random selection

As in the systematic procedures again two- to four-point-averages were calculated. For example a four-point-average was obtained by taking four random single estimates, each from the full series of twelve. Thus, it was possible to select, by chance, the same value four times. This random selection was not completely analogous to four injections at the same phase in the ventilatory cycle, because the estimates would then have been mutually different due to instability of the patients and measurement errors.

Statistical analysis

p-levels for differences between measurements within the same patient were calculated according to a paired Student’s t-test for small samples. Significance was determined at $p < 0.05$.

Results

In all nine patients the haemodynamic variables (Table 1) were stable for the series of 12 observations. Mean values ±SD were for radial artery pressure $89 ± 5$ mmHg, pulmonary arterial pressure $19 ± 4$ mmHg, and central venous pressure $9 ± 1$ mmHg.

After sorting the series of 12 measurements with respect to the moments of injection in the ventilatory cycle a cyclic pattern of modulation of the estimates appeared. Figure 2 shows the results of three selected series of 12 CO estimates for 3 patients. All these patterns of modulation have the same periodicity as the ventilation, but are shifted in phase ($\Phi$) and have different amplitudes of variation. In this figure we have indicated the point where the curves crossed the 100% line in the negative direction.

This point has been expressed as a percentage of the whole cycle, starting with insufflation. In agreement with this figure for three patients we observed marked differences in the amplitude and the phase of the pattern of modulation for all patients.

The variance in the phase ($\Phi$) for the nine patients is given in Table 2, together with the minimum $\text{CO}_{\text{min}}$ and maximum ($\text{CO}_{\text{max}}$) values of the single estimates in percentages of the mean cardiac output. The maximum dif-