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Continuous Cardiac Output Catheters

Delay in In Vitro Response Time after Controlled Flow Changes

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CONTINUOUS measurement of cardiac output (CO) may improve the timely treatment of high-risk patients.^{1,2} The available continuous CO (CCO) monitors measure CO by a modified thermodilution technique using a filament to generate heat. The two marketed CCO monitors are the CCO/oximetry "Vigilance" thermodilution catheter (Baxter, Deerfield, IL) and the "Opti-Q" mixed venous oxygen saturation (\bar{Sv}_{O_2})/CCO catheter (Abbott, Abbott Park, IL). The thermal signal, the signal-to-noise ratio, and thermal noise affect the accuracy of the systems. Differences in the heated element, the thermal signal, the signal-to-noise ratio, and thermal noise affect the accuracy of the systems. The purpose of this study was to compare *in vitro* response times of these catheters to different flow rates, temperatures, and thermal noise.

Methods

A CCO pulmonary artery catheter inserted into a rubber cast the size of the superior vena cava, the right ventricle, and the pulmonary artery was placed in a custom-made flow bath containing 30 l of pumped nor-

mal saline. The Abbott Opti-Q \bar{Sv}_{O_2} /CCO thermodilution catheter (Model 52509; 8 French, 110 cm; software version 1.08) has a 15-cm thermal coil. The Baxter CCO/Oximetry (\bar{Sv}_{O_2}) catheter (model 744H; 7.5 French, 110 cm; software version 4.42) has an 11-cm thermal filament.

The response time to changes in flow was tested during different conditions. Bath temperatures were accurate to $\pm 0.3^\circ\text{C}$, flow rates were accurate to ± 0.32 l/min, each change in CO was maintained for 30 min, and the displayed CCO value was recorded every 20 s. Baseline measurements were obtained after a 30-min stabilization period at 37°C and a flow rate of 3 l/min. Flow was increased to 7 l/min and then decreased to 3 l/min (fig. 1). Flow was increased to 5, 7, and 9 l/min and then decreased to 7, 5, and 3 l/min. Three catheters of each type were studied separately, and the experiment was repeated at 35°C and 39°C . The effect of a slower change in CO at 37°C was evaluated by changing flow from 3 to 7 l/min and from 7 to 3 l/min in steps of 1 l/min every 2 min.

In a separate series of catheters, baseline fluctuations in pulmonary artery temperature, previously recorded from 13 Stanford University Hospital intensive care unit patients, were used to superimpose "thermal noise" on the pump system. Stabilization for 60 min occurred, and then changes in flow from 3 to 7 l/min and back to 3 l/min were evaluated.

Data Analysis

The time delay between flow change and the display of 20, 50, and 80% of maximal CCO change was noted, as described by Siegel *et al.*³ These values have clinical usefulness as detecting change (20% change), magnitude of change (50% change), and total change (80% change). Data from three catheters of each type were combined and analyzed by analysis of variance and the Newman-Keuls test, with a probability value < 0.05 considered significant.

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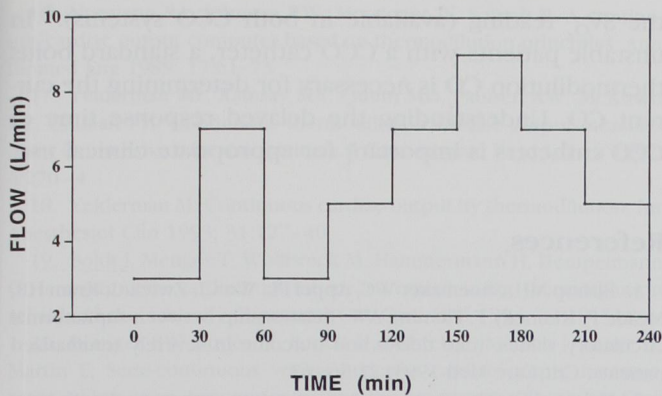


Fig. 1. Diagram of the changes in flow over time. A flow rate of 3 l/min was maintained for the initial 30 min. Flow was then increased to 7 l/min for 30 min, followed by a decrease to 3 l/min for 30 min. Flow was then increased to 5, 7, and 9 l/min for 30 min each and then decreased to 7, 5, and 3 l/min for 30 min each.

Results

There were 6,340 recorded CO values. At 37°C, when flow increased from 3 to 7 l/min, the eventual increase in CCO was 4.14 ± 0.25 l/min for the Abbott catheter and 4.16 ± 0.19 l/min for the Baxter catheter. However, both catheters showed a 4 to 5 min delay in response time (fig. 2). When flow decreased to 3 l/min, a 50% change occurred at 4 to 5 min with the Abbott catheter and at 10 min with the Baxter catheter. Combining the data for the six 2-l/min flow rate changes, the 20, 50, and 80% response times for the Abbott and Baxter catheters were 2.9 ± 0.2 min versus 3.3 ± 0.3 min; 3.9 ± 0.1 min versus 6.6 ± 0.8 min ($P < 0.01$); and 4.7 ± 0.2 min versus 11.2 ± 1.1 min ($P < 0.01$), respectively.

For flow changes (increases and decreases combined) between 3 and 7 l/min at 35°C, the Abbott versus Baxter catheters had 20, 50 and 80% change at the following times: 3.5 ± 0.2 min versus 4.8 ± 0.7 min ($P < 0.05$); 4.1 ± 0.2 min versus 6.7 ± 1.0 min ($P < 0.05$); and 4.9 ± 0.3 min versus 11.7 ± 3.2 min ($P < 0.05$), respectively. At 39°C, changes at these time points for Abbott versus Baxter were 3.7 ± 0.3 min versus 4.5 ± 0.6 min; 4.3 ± 0.3 min versus 5.9 ± 0.4 min ($P < 0.05$); and 5.3 ± 0.4 min versus 6.5 ± 0.3 min ($P < 0.05$), respectively. With superimposed thermal noise, both systems needed more than 30 min for stabilization at constant flow. With thermal noise, combined changes for the three time points for Abbott versus Baxter catheter were 4.5 ± 0.5 min versus 10.8 ± 0.6 min ($P < 0.05$); 6.5 ± 0.2 min versus 13.5 ± 4.4 min ($P < 0.05$) and 10.2 ± 1.5 min versus 20.1 ± 4.2 min ($P < 0.05$),

respectively. A clinically relevant delay in response time occurs with both catheters.

When flow was changed by 1 l/min every 2 min, no catheter detected the change within that 2-min time period. Therefore, the response times for the change from 3 to 7 l/min over the 8-min time period were analyzed as a single flow change. For the Abbott and Baxter catheters the 20, 50, and 80% response times were 5.3 ± 0.1 min versus 6.5 ± 0.8 min; 8.8 ± 0.1 min versus 7.6 ± 0.6 min, and 11.1 ± 1.1 min versus 10.8 ± 0.3 min, respectively.

Discussion

Noninvasive CCO systems include transthoracic electrical bioimpedance,^{4,5} suprasternal continuous-wave Doppler ultrasonography,⁶ and transcutaneous continuous-wave ultrasonic Doppler.^{7,8} Although studies have suggested limited accuracy of these devices in clinical use, Thangathurai *et al.*⁹ noted improved performance of the recent thoracic bioimpedance device. Continuous, invasive methods include transesophageal Doppler,^{10,11} transtracheal Doppler,^{12,13} transesophageal Doppler echocardiography,¹⁴ and automated border detection.¹⁵ The Baxter CCO catheter has comparable accuracy compared with standard thermodilution CO in stable surgical and critically ill patients.¹⁶⁻²² Its reliability has been questioned with cold-fluid infusion,²³ after hypothermic cardiopulmonary bypass,²⁴ and in postreperfusion of liver transplantation.²⁵ Response time delays of 5-7 min have been shown in sheep during hemodynamic changes³ and in critically ill patients.²³ The Abbott catheter has been shown to be accurate in stable patients,²⁶ but its response time has not been studied previously.

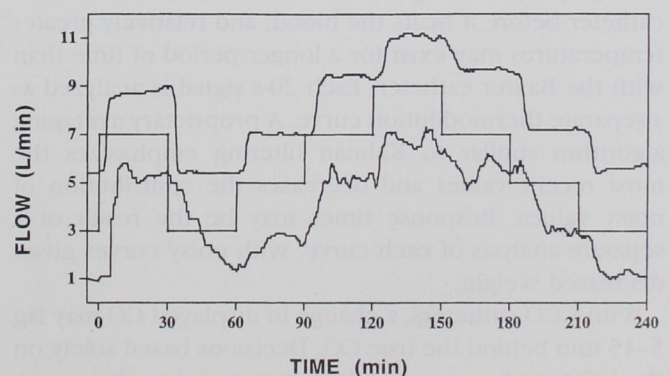


Fig. 2. Response of a representative Abbott and Baxter catheter to changes in flow. The set flow is displayed on the middle line. For visual clarity, the Abbott catheter readings are offset by +2 l/min and the Baxter catheter readings are offset by -2 l/min.

The CCO catheters used in the current study measure CO by modified thermodilution, whereby a thermal element intermittently warms the blood with a small amount of heat ("hot thermodilution"). In the current study, both systems had significant response delays that can be explained by their measuring techniques (see below). In addition, both catheters showed markedly prolonged response times when fluctuations in pulmonary artery temperature (thermal noise) were superimposed on the thermistor readings. In patients, thermal noise arises from ventilation, movement, and inflation/deflation of sequential compression stockings. Thermal noise may be larger than the thermal signal, resulting in a longer analysis period. Therefore, when CO acutely changes, the systems may not readily detect that change as separate from the variability of the previous measurements.

These two systems have different design features. The Baxter "Vigilance" CCO monitor has a flat heating filament that is activated for 1–4 s using a pseudorandom binary sequence to produce constant heat signals emitting 15 W of heat.²⁷ The resulting multiple superimposed signals are analyzed stochastically to determine a single thermodilution curve that is applicable to an entire set of data. It may be resistant to baseline thermal drift and intermittent thermal changes. However, the system may not be able to analyze rapid changes in CO because a single thermodilution curve will not be simultaneously applicable to data surrounding the CO change. Therefore, the system may require a long time delay until an adequate set of data has been collected at the new CO value.

The Abbott "Q-vue" system uses a coiled filament that emits heat for 20 s of a 40-s repetitive on-off cycle; the average power during the 40 s is 6 W. The coil heats the catheter before it heats the blood, and relatively greater temperatures may exist for a longer period of time than with the Baxter catheter. Each 20-s signal is analyzed as a separate thermodilution curve. A proprietary averaging algorithm similar to Kalman filtering emphasizes the most recent values and decreases the contribution of noisy values. Response times may be the result of a separate analysis of each curve, with noisy curves given decreased weight.

With CCO catheters, a change in displayed CO may lag 5–15 min behind the true CO. Decisions based solely on the CCO reading may result in inappropriate therapy. A better assessment of acute changes in CO may include a combination of the CCO reading, available hemodynamic parameters (heart rate and blood pressure), and

the SvO_2 reading (available in both CCO systems).² In unstable patients with a CCO catheter, a standard bolus thermodilution CO is necessary for determining the current CO. Understanding the delayed response time of CCO catheters is important for appropriate clinical use.

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