Flow Bench for the Evaluation of Thermal Dilution Cardiac Output Computers

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INTRODUCTION

The use of cardiac output computers has become a common practice as an adjunct in the treatment of the critically ill. Often the evaluation of these instruments is performed *in vivo* where thermistor position and mobility, respiratory variation, hemodynamics, and indicator handling are uncontrolled. Comparisons between multiple injections, dye-dilution determinations, or with Fick determinations are usually the means by which the performance of these units is analyzed[1,2]. The major drawback to all of these methods is in the assumption of hemodynamic stability over the time course necessary to make a determination[3,4]. In clinical experience, these determinations are usually performed on patients sufficiently unstable to warrant the insertion of a Swain-Ganz catheter. Animal trials are subject to the same instabilities but the problems are compounded by the improper use of thermistor catheters designed for the human central venous anatomy and not compatible with the animal models (e.g.-CVP lumen in the vena cavae).

The construction of this flow bench was undertaken with the objective of eliminating the artifacts and random variation inherent in *in vivo* preparations by employing a more controllable mechanical simulator. Good performance of a computer in this idealized circulatory system is a necessary prerequisite for good clinical performance, and a poor result on this simulator will be a reflection of its poor clinical performance.

Cardiovascular research laboratories routinely utilize a pump and a graduated collection container as the most facile and reliable combination of instruments for the calibration of flow probes. Applying the same principles with modification, this system was constructed and is currently used to test the accuracy of cardiac output computers. (Figure 1)

MATERIALS

A Bentley Pediatric Oxygenator, model Q-110, with integral heat exchanger is utilized for the maintenance of an adequate reservoir and physiological temperatures. The oxygenating capabilities of this unit were not employed in order to minimize hemolysis. A Sarns Normothermia Control Module is used to supply the heat exchanger with an adequate quantity of temperature regulated distilled water to eliminate thermal variation in the circulating medium. (Figure 2)

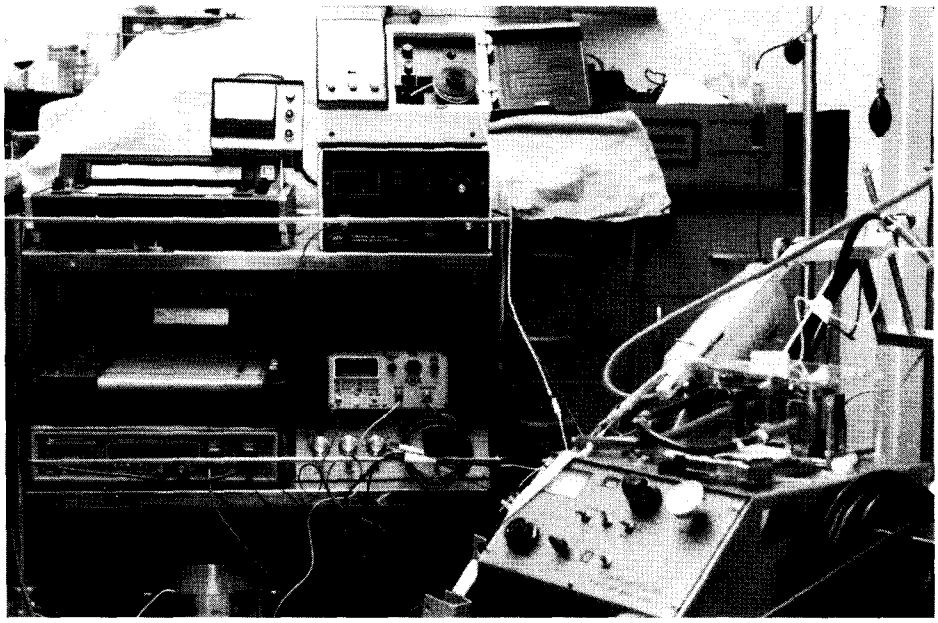

Figure 1 (above)
Multi-Unit Testing Arrangement

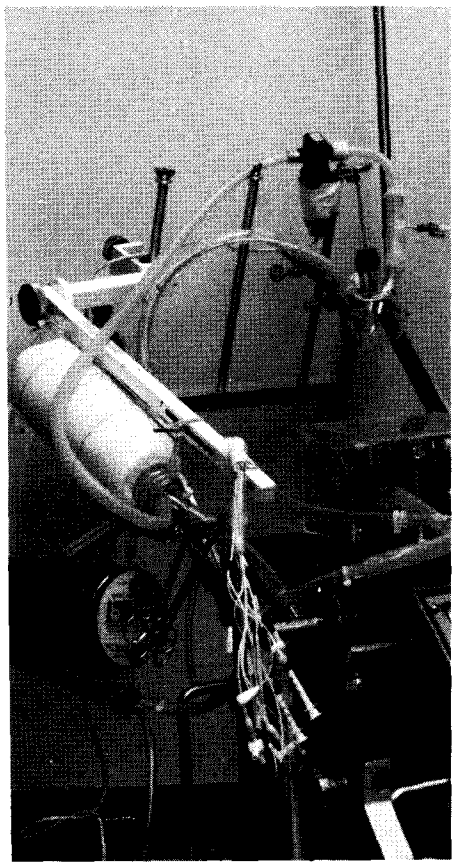

Figure 2 (left)
Flow Bench Prior to Loading

An extracorporeal, electromagnetic flow measuring system, the Biotronex BL610, is calibrated using outdated human bank blood (hematocrit 35±5%) by the method of timed volume collections to an accuracy of ±2%. (Fig. 3) The electromagnetic flowmeter may subsequently be used as a reference to which any test unit can be compared.

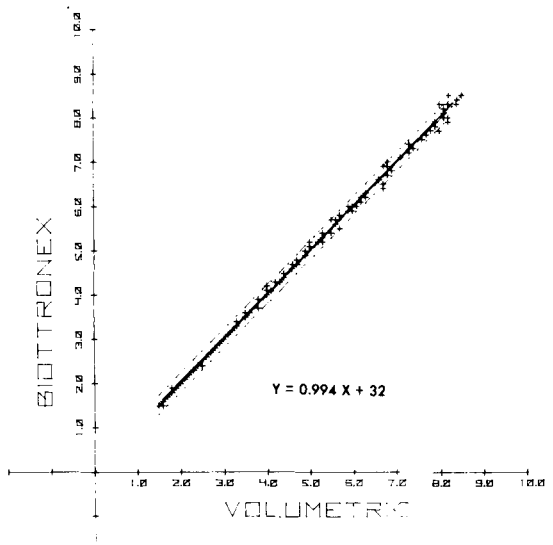

Figure 3

The "ventricle" of the flow bench (Fig. 4) is a 200 ml., 3 port, glass distilling flask incorporating a thermometer in the central port as a check on temperature control. Since adequate mixing is essential[5-8], the cage (ball removed) of a prosthetic aortic valve is inserted in the proximal port so as to initiate mixing prior to indicator entry into the "ventricle". A large bore (33mm OD x 29mm ID) 15 cm. length of polyvinyl chloride (PVC) tubing, approximating pulmonary artery diameter, is attached to the distal port of the "ventricle". This simulated pulmonary artery was designed to prevent thermistor contact with the chamber walls and to avoid changes (though insignificant) of the temperature dissipation constant of the thermistor due to the increased velocity required to transport the circulating fluid through a smaller bore measuring chamber[9]. All of the "ventricle" components were rigidly fastened and sealed using Silicone Type A Medical Adhesive*. The flow probe is placed distal to the measuring chamber.

The Swan-Ganz catheter(s) is threaded through either PVC or silastic tubing so that 70cm. of the catheter is immersed in the circulation as in human use. It is passed through the proximal port of the "ventricle" and terminates in the measuring chamber. The catheter's position is fixed so that errors due to thermistor-wall contact[9,10] are eliminated.

*Dow-Corning Corp.

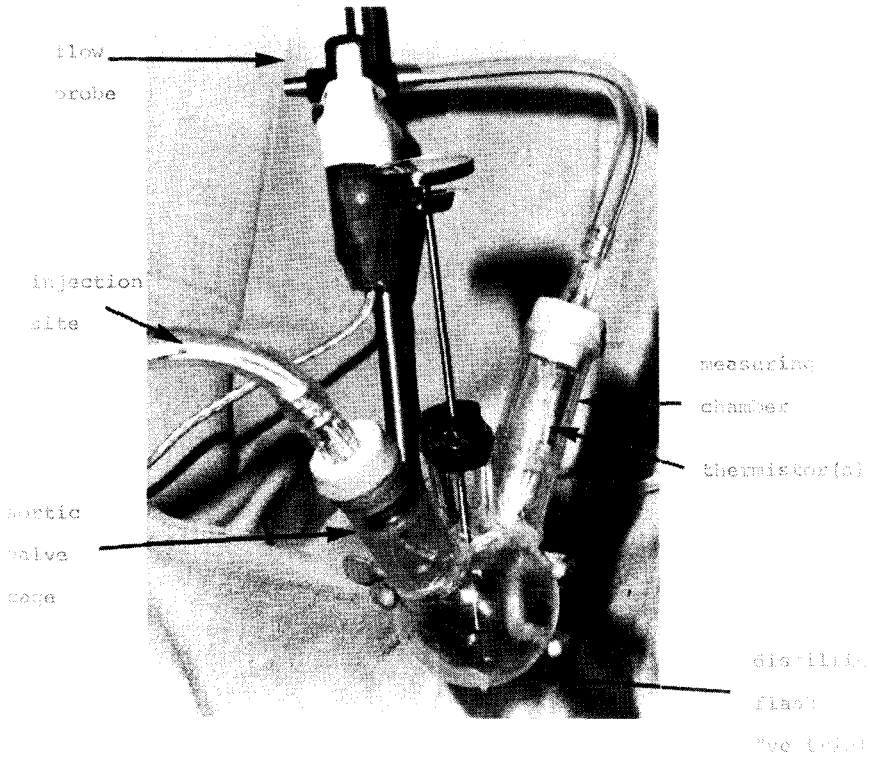

Figure 4 "Ventricle" Schematic

PVC or silastic tubing is used for all circulatory pathways and polycarbonate connectors and/or silastic medical adhesive is used to secure all connections. An occlusively set roller pump is the drive system used.

It is necessary to record output curves from the computer(s) in order to eliminate those that demonstrate unstable baselines or unusual artifacts.

DISCUSSION

The rationale for the use of a non-pulsatile apparatus, the roller pump, to verify the accuracy of cardiac output computers is found in the Stewart-Hamilton equation. This equation, used as the basis for computation of indicator dilution cardiac output determinations, is, in fact, a constant flow equation. Cropp and Burton[5] reported that the washout curve recorded distal to an effective mixing region is essentially exponential for steady state and pulsatile flow provided the stroke volume and rate of flow remain unchanged. Therefore, the Stewart-Hamilton equation can give accurate mean flow measurements under appropriate conditions for both types of flow.

Certain attempts at approximating the physiological model must be made when it is thought that deviation from physiological design would serve to confuse the signal relayed by the thermistor to the computer. The most important approximation, particularly in the testing of thermal-dilution computers, is that of maintenance physiological temperatures with variations equal to or less than those present *in vivo*. With the heat exchanging devices used in this model, the temperatures drift downward at the rate of .03°C./min. during the time that the normothermia unit is not in its heating phase. (During the active heating phase, thermal-dilution determinations are not possible). This compares favorably with the documented variation between the right atrium and the pulmonary artery of .033°C.[7] and the temperature variation in the pulmonary artery during spontaneous ventilation of .06°C. (this value is higher in the artificially ventilated organism)[11-13]. Since the lengthiest determination requires less than 30 seconds (a flow of 1.5 liters/min.), a temperature variation of greater than .015°C. is unlikely during the course of any determination performed with this bench.

The "ventricle" was made to approximate right heart volume, the physiological mixing chamber, in order to minimize effects of thermistor non-linearity and temperature dissipation constant that may result by mixing of the indicator in an inadequate volume of circulating fluid. All circulatory pathways were composed of silastic, PVC, and glass, all better insulators than the tissue of the central venous system, thereby minimizing loss of indicator from the system.

Measuring flow through a mechanical circulation rather than the intact animal has the advantage of eliminating errors due to uncontrollable physiologic variation. Among the major sources of these errors are;

1. Respiratory Variation: This is generally believed to be two distinct artifacts; that of actual temperature variation resulting from normal breathing[9,11-13] and fluctuations due to thermistor contact with the vessel walls[9,10]. Other more observable events are sighing, hiccups, and eructation.
2. Hemodynamic Instability: This is primarily a problem of clinical trials (though not infrequent in animal preparations) resulting from cardiac irritability and patient excitation[3], including patient agitation not uncommonly associated with awareness that an invasive maneuver is imminent.
3. Indicator Handling: With thermal indicators, handling must be careful and consistent. This presents a particular problem when aseptic technique must be maintained. There is the obvious difficulty with maintaining consistent transit times between removal of the indicator from its temperature source and injection through the catheter. A not uncommon error due to indicator mishandling is the deterioration in the exponential decay of a curve when the residual indicator remaining in the catheter after injection is not withdrawn by aspirating a volume equal to that of the catheter lumen (~1cc). Aspiration of this residual indicator prevents prolonged heat exchange between the catheter and the circulating blood.
4. Catheter Variability: Though variations in thermal response of commercially produced catheters has not been studied, a distinct advantage of the flow bench is that innumerable determinations can be performed before catheter failure necessitates a change in thermistor. *In vivo* studies would

require a change in thermistor catheter with each subject studied.

5. In the clinical situation, the "standards" against which thermal-dilution computers are being compared have inherent errors of 10-20%; at least as great as the error of the thermal-dilution method. The flow bench enables the employment of a sensitive "standard", the in-line electromagnetic flowmeter, with which computer output can be compared.

SUMMARY

The flow bench described here has been used to determine the accuracy and reliability of eight different thermal-dilution cardiac output computers from five manufacturers. It was found to be sufficiently sensitive to elucidate at least six defects in the manufacture, design or calibration of these units as they arrive from the factory (Fig. 3a-e). The sensitivity was such that variation in the performance of these units is evident and significant (Table 1).

One study of a dye-dilution computer was undertaken with good results. Only thirty determinations were performed and it is unknown to us, at this time, at what intensity of background dye it would be impossible to distinguish the indicator signal from the background dye. More tests are necessary to determine the limits of this model for testing dye-dilution systems.

Figure 3a

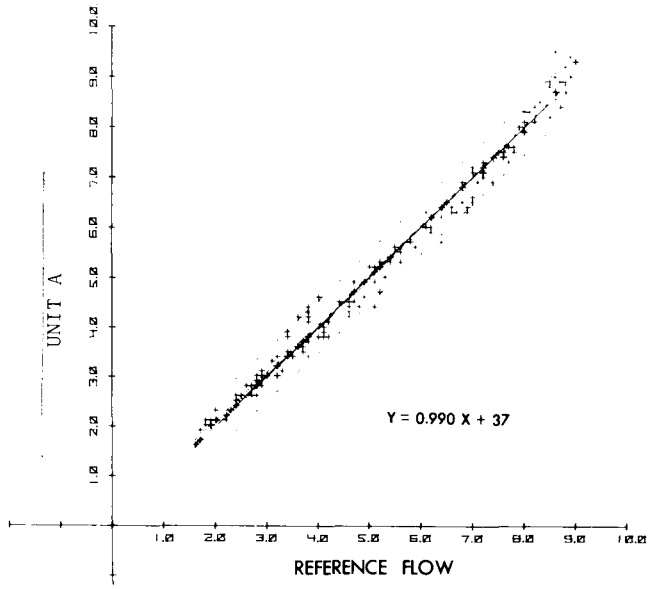

Figure 3b

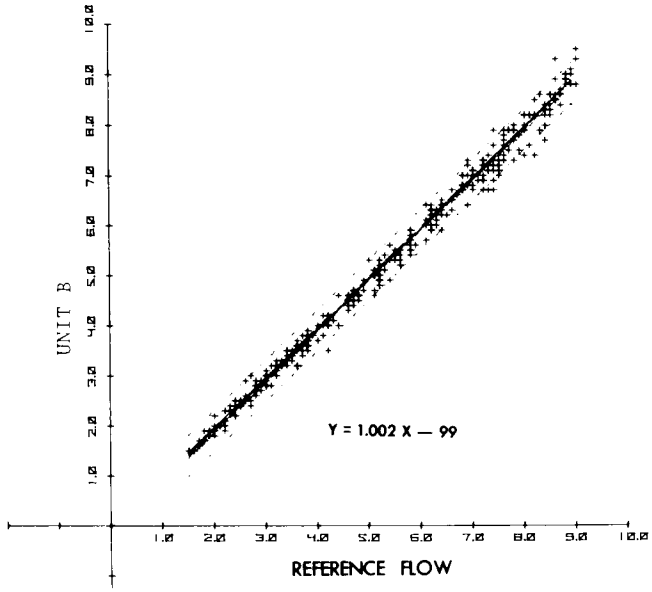

Figure 3c

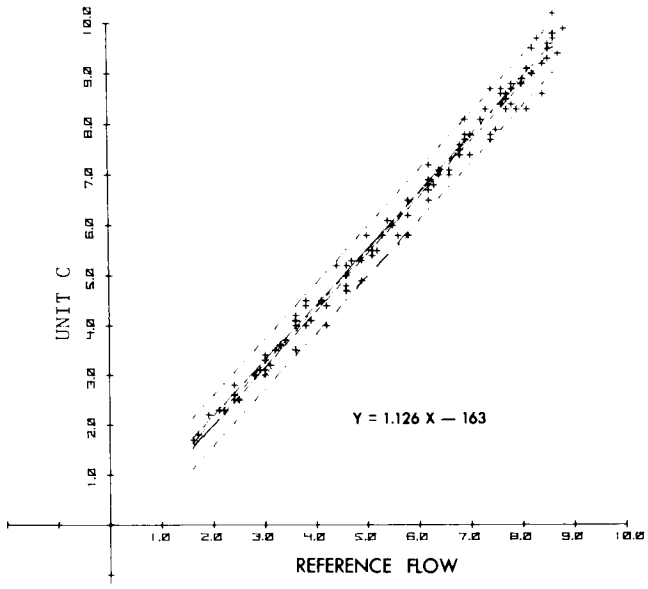

Figure 3d

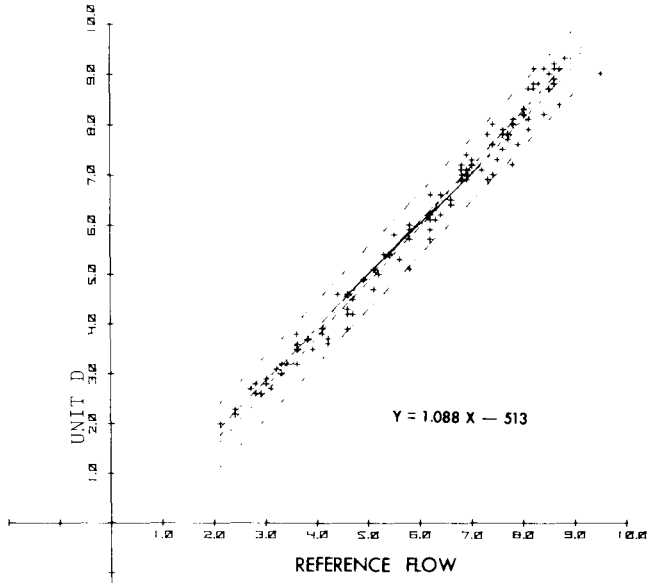

Figure 3e

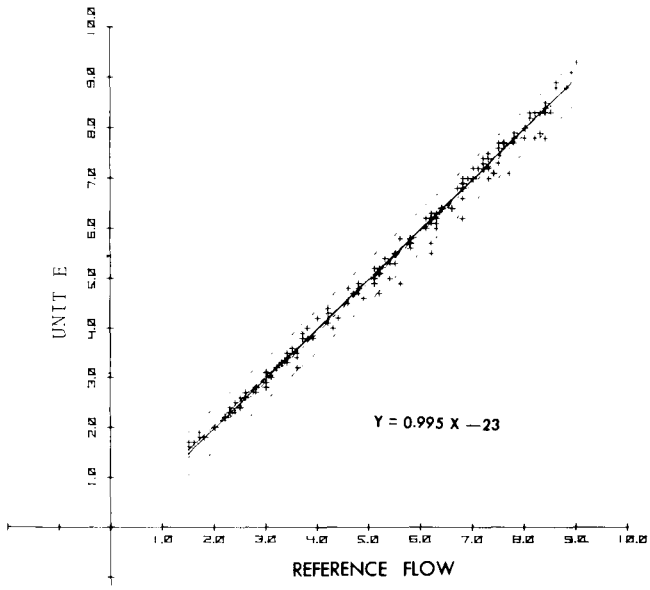

Table 1

REGRESSION EQUATIONS FOR CARDIAC OUTPUT COMPUTERS

UNIT	REGRESSION EQUATION	R^2
A	$Q_{meas} = 0.990\ Q_{act} + 37$	0.984
B	$Q_{meas} = 1.002\ Q_{act} - 99$	0.991
C	$Q_{meas} = 1.126\ Q_{act} - 163$	0.989
D	$Q_{meas} = 1.088\ Q_{act} - 513$	0.978
E	$Q_{meas} = 0.995\ Q_{act} - 23$	0.989

This cardiac output computer test bench was constructed almost entirely from elements commonly associated with cardiovascular research laboratories, thus eliminating excessive expenditures in the testing of an instrument upon which much research data depends on.

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