Measurement of Cardiac Output Using the Photoelectric Earpiece: A Comparison with Simultaneous Fick Measurements

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Since the early studies by Hamilton, Werko, and Doyle, and their colleagues, a variety of indicator dilution techniques have been developed for measuring the cardiac output in man. The most widely accepted have been those requiring the use of the continuously recording cuvette densitometer. Numerous studies have appeared to demonstrate close correlation of values by the Hamilton and by the standard Fick methods.

Despite the obvious advantages of simplicity and ease of performance the use of the photoelectric earpiece for quantitative studies has been cautious. This has occurred not only because of theoretical objections related to the reliability of the ear as an arterial sampling site, but particularly because of the lack of a suitable electronic amplifier and earpiece. Recently the earpiece has enjoyed increasing acceptance for routine use. A number of studies have appeared comparing simultaneous cardiac output determinations from cuvette densitometer curves with those from the earpiece and the correlation has been quite satisfactory.

With the development of new recording equipment which is both sensitive and stable and the introduction of Coomassie Blue dye we have been able to reassess the earpiece technique. This paper compares cardiac output measurements from earpiece dye curves with simultaneous Fick outputs, and describes a modified technique for injection and recording with "end-tail" calibration of curves which has proved extremely simple and reproducible.

Methods

The study was divided into three parts: 1) Fick and Coomassie Blue dye determinations of cardiac output were carried out in 27 patients with congenital or rheumatic heart disease ranging in age from five to fifty-five years. In 13 of these subjects the measurements were simultaneous, in 14, within one hour. 2) In another group of 25 patients the initial Fick determination was followed by a second Fick, making certain that basal conditions existed for both. Most of these studies were within 30 minutes; all were within one hour. 3) In the first 27 patients, curves were recorded as the catheter was withdrawn and injections made into each of the right-sided cardiac chambers. These curves were compared to show reproducibility.

For the Fick determinations, arterial and venous blood samples were estimated for oxygen saturation by a Waters-Conley oximeter and confirmed by the Van Slyke method. Gas samples were analyzed by the Scholander technique, and oxygen consumption calculated by the method of Haldane and Priestley.

The Cambridge photoelectric red-infrared earpiece and the amplifier and servo-direct writing recorder of the Cambridge Mark II unit were used. The response time was 0.8 seconds for 90% of full-scale deflection. Using the linearity correction charts supplied for the Mark II, the concentration of dye could be read with a high degree of accuracy extending to a concentration of Coomassie Blue of up to 100 mg per liter of blood. An average injecting dose of 0.5 to 1.0 mg of Coomassie Blue dye per kilogram of body weight has been used. An injectate of 60 mg was not exceeded for any one dye curve and the largest total amount of dye used in any one patient was approximately 600 mg.
Injection apparatus and technique: The cardiac catheter, F, is first flushed, and the injecting syringe, A, filled, from the saline reservoir, B. The polyethylene tubing, D, is filled from the dye reservoir, C, by flushing through its distal stopcock located at E, and the reservoir, C, is cut out of the circuit. The measured volume of dye in the tubing, D, is then flushed through the catheter. An electronic injection marker is located on the injecting syringe, A.

The earpiece was adjusted to the pinna of one ear allowing the pressure on the ear to be set by the tension of the spring incorporated into the instrument. It was important that the earpiece not be covered in order to insure adequate ventilation and prevent overheating. A series of injections of 2% Coomassie Blue dye was made through a Rodriguez 125 cm cardiac catheter by rapid "slug" injection. Injection time has been recorded by an electronic switch on the injecting syringe seen in figure 1. A polyethylene tubing joined to the intracardiac catheter was filled carefully with dye by a sidearm with stopcock. Combinations of tubings with capacities of 0.5 to 3.0 ml have allowed selection of a dye dose between 10 and 60 mg. The dye was washed through rapidly with 10 ml of saline. On repeated trials in vitro the injection time of the total dye bolus has been under 0.2 second. The technique has been simple enough to allow accurate repetition of the same injectate with an estimated error of under 2% for serial curves. It also provided a method for using the same volume of dye for dilution in making up calibration standards after the catheterization was over. Since the same volume of dye was used for both injectate and calibration, the exact measurement in mg was unnecessary. Dye curves were calibrated by the end-tail method, and a 7 ml blood sample has been drawn approximately 90 seconds after the injection of dye, when the tail of the curve has stabilized. The blood has been allowed to clot and the dye read directly from the serum in a Beckman DU model spectro-photometer at 585 millimicrons. There has been no need for dye extraction. The technique for the spectrophotometric determination of Coomassie Blue dye in this laboratory will be described separately.

Comparison of earpiece dye dilution and simultaneous Fick cardiac outputs in 27 patients. Average dye CO 4.2 l/min. Average Fick CO 4.2 l/min. r = 0.93.

Time components of the curve have been compared using the nomenclature of Wood and Swan. All curves have been plotted semilogarithmically for use in calculation of cardiac output by the method of Hamilton.

Results
Fick dye determinations were carried out in 27 patients and the results were graphed (fig. 2). In 13 of these patients the determinations were simultaneous; in 14 patients the studies were within an hour. The correlation coefficient of Fick to dye for the 27 patients was 0.93. The correlation coefficient for Fick to dye when done simultaneously was 0.97. The average dye cardiac output for the 27 patients was 4.2 l/min; the average Fick cardiac output in the same group was 4.2 l/min. In the 13 patients done simultaneously the average dye output was 4.0 l/min as compared with 4.1 l/min by the Fick. There is no significant difference between the means of these two groups.

For the 25 patients in whom a Fick to Fick comparison was made the correlation coefficient was 0.87 (fig. 3). The average of the initial Fick determination was 4.35 l/min; the average of the second Fick determination was 4.34 l/min. Even though there were individual variations approaching 1.0 l/min in some cases, the reproducibility of the Fick
Comparison of two successive Fick cardiac output measurements in 25 patients. $r = 0.87$.

The average Fick cardiac output plotted against each of the two observed successive Fick determinations in 25 patients.

determination is of the same order of magnitude as that of the dye measurement. Figure 3 shows the correlation of the two Fick determinations done in the second group of patients. Because the average Fick is probably a more valid observation than either determination alone, the average of the two Fick procedures is plotted against each individual Fick value (fig. 4).

For the 66 determinations for comparison of dye to dye outputs in the original 27 patients, a correlation coefficient of 0.96 was calculated. Figure 5 shows the individual serial cardiac outputs plotted against their average for each patient. In this figure each vertical series of dots represents one patient, demonstrating the reproducibility of the method as compared with figure 4. Confidence lines of $\pm 25\%$ were drawn on all graphs.

Discussion

The results of these studies demonstrate a satisfactory empirical comparison of cardiac output measurements by the earpiece dye dilution and the standard Fick methods. With the exception of one patient, all values fell within 15% confidence limits, and in this patient there is good reason to doubt the Fick value. This Fick-earpiece correlation closely approximates the results reported for Fick and cuvette techniques.$^{7-9}$ The inclusion of Fick to dye outputs recorded within one hour did not change significantly the correlation coefficient from those measurements done simultaneously, suggesting that the cardiac outputs of these patients did not change appreciably, and that a "basal" state had been reached.
The reproducibility of the Fick method in this laboratory compares well with that reported in the studies of Thomasson and of Richardson and his associates. The reproducibility of the serial earpiece dye dilution cardiac output determinations is at least as faithful as that reported by McGregor, and by Sleeper, and their associates for simultaneous cuvette densitometer studies. It also compares well with the studies reported by Bruce, and by Gabe, and their colleagues for earpiece-cuvette cardiac output measurements. The study confirms the work of Taylor who also compared Fick measurements with dye dilution cardiac outputs using the same earpiece.

The reliability of the ear as an arterial sampling site, and the comparison of the earpiece and arterial cuvette dye curves, has been reported in detail previously. The differences in “distortion” sometimes seen between the dilution curves from earpiece and cuvette densitometer should pose no problem in the calculation of cardiac output provided a definitive downslope can be inscribed before the onset of recirculation, and provided the measured injectate can be fully delivered to the patient. The density of color of Coomassie Blue dye is so great that we have found significant error in the drawing up of dye into a calibrated syringe. This appeared to be due to inability to read the level of dye accurately, and to hidden trapped air bubbles in the syringe. However, the method outlined, using a length of stiff polyethylene tubing, obviates the laborious measurement of dye in the injecting syringe and simplifies the procedure greatly. Using multiple injections in vitro, flushing through the same tubing we have found less than a 2% error in delivering the desired amount of dye injectate.

The major advantages of Coomassie Blue dye over indocyanine green include its ready solubility and stability in dilute aqueous solutions as well as in blood. Indocyanine green is cleared much too rapidly for accurate end-tail calibration methods. The studies of Taylor and Thorp have shown that the clearance of Coomassie Blue dye is rapid enough that there is no permanent skin discoloration as there is with Evans Blue, yet slow enough to allow calibration of curves by the end-tail method. The disappearance of the dye from the blood is also slow enough that there is no appreciable difference between arterial and venous samples if drawn simultaneously within the period of stable baseline. We used an arterial sample taken within 90 seconds after injection in these studies. However, venous samples can be drawn for accurate calibration if more time is allowed for equilibration of the dye in the circulation. This advantage makes the dye suitable for the study of cardiac output where estimations of blood dye concentration must be made from venous samples alone, and no arterial puncture is planned. In these cases the dye can be injected into one peripheral vein and an end-tail venous sample from another site analyzed.

A major step in the simplification of the calibration procedure has been the ability to measure the blue dye in the undiluted serum by the Beckman DU spectro-photometer. The laborious method of extraction of dye from the serum was not necessary in our experience. In addition, since the identical volume of dye in the polyethylene tubing is used to make up the standards, calculation of the exact injectate in milligrams is unnecessary.

The limitations of the method center about the stability of the baseline, and the error involved in measuring the tail of the curve. An error of 1.0 cm in the measurement of the tail produces a 10% error in the calculation of cardiac output. As noted by Bruce, however, the likelihood of change in baseline is minimal under one minute, although it does occur in three to five minutes. The most common cause of baseline instability is movement of the earpiece with respect to the pinna of the ear. The optical density of the vascular bed overlying the photocells must remain constant. We have found that cardiac output studies can be carried out during vigorous exercise if the earpiece is simply taped to the

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Occasional changes in oxygen saturation due to respiration with resulting regular baseline variations have been seen, making it necessary to administer oxygen to a few patients. However, the comparatively larger doses of dye injectate and somewhat reduced sensitivity of the recording system have overcome this problem in a majority of cases. Administration of oxygen prior to each curve has been unnecessary. A total of 600 mg of dye in any one patient has not been exceeded, and there have been no major toxic manifestations in more than 185 patients with a total of over 660 dye curves. Transient episodes of vomiting have occurred in one or two highly apprehensive patients at intervals following large doses of dye, but these patients were inclined to be nauseated due to premedication.

The validity of the method requires that the response of the earpiece be linear during the buildup of dye background. With the Cambridge Mark II an adjustment for background dye is made automatically before each injection. In one of the patients in the original Fick-dye series who was a Negro and in several other dark-skinned patients there appeared to be no difficulty in recording an adequate dye curve from the Cambridge earpiece. We have used the same earpiece on the tongue of the dog in animal experiments and have found excellent correlation of simultaneous Fick-earpiece cardiac output determinations. These studies are being pursued further.

Under the conditions mentioned, and using the Cambridge earpiece, amplifier and recorder, we have found the earpiece dye technique to be a convenient and reliable method for measuring cardiac output. The obvious advantages of ease of performance and repeatability at frequent intervals with reasonable accuracy, and without the need of a constant withdrawal apparatus, would seem to establish this particular earpiece as a reliable quantitative tool for the study of Coomassie Blue dye curves.

Conclusions
Earpiece dye dilution cardiac output measurements have been compared with the Fick in 27 patients. The correlation has proved to be comparable to that of simultaneous cuvette densitometer-Fick studies previously reported. Modified techniques for injection of Coomassie Blue dye and calibration by the end-tail method have simplified the procedure greatly. The Cambridge earpiece has been shown to be a reliable quantitative tool in this laboratory.

References
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