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A new technique for repeated measurement of cardiac output during cardiopulmonary resuscitation

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ABSTRACT

The authors have developed a method for measurement of cardiac output during CPR with ventricular fibrillation. The method avoids the problems encountered when conventional techniques are used under the conditions of very low cardiac output. The method consists of rapidly injecting 5% saline as the indicator into the left ventricular cavity and detecting its appearance in the descending aorta by withdrawing aortic blood through an electrically calibrated conductivity cell. The adequacy of indicator mixing has been verified by obtaining dilution curves simultaneously from the brachial and femoral arteries. Cardiac output can be determined even when output is as low as 7 ml/min/kg during CPR with ventricular fibrillation. Repeated determinations can be made as often as every min. This method offers promise as a practical research tool. which can also be used with dye indicators.

Key words: animal model, artificial circulation, blood flow, CPR, perfusion

INTRODUCTION

One objective of cardiopulmonary resuscitation (CPR) is to produce a cardiac output sufficiently large to maintain acceptable perfusion of the vital organs. The evaluation of new techniques to enhance cardiac output during CPR requires measurement of the cardiac output under low output conditions. With the traditional indicator dilution method, it is very difficult to process the dilution curves with very low cardiac output. The dilution curve is broad and of low amplitude; recirculation of indicator tends to occur before the full curve has been inscribed. This paper reports an indicator dilution method that minimizes these difficulties and allows repeated determinations of very low cardiac output without accumulation of large intravascular concentrations of indicator.

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METHOD

The method employs 5% NaCl solution as the indicator and an electrically calibrated, flow-through conductivity cell as the detector. Saline indicator is forcibly injected into the left ventricle and detected in the descending aorta (Fig. 1). When conventional injection and sampling sites are used, there is significant loss of indicator from capillary beds resulting in a low amplitude dilution curve. With the left ventricular injection and aortic sampling method, however, indicator loss does not occur because there is no intervening capillary bed. Therefore, rapid clearance of indicator elsewhere becomes an asset, permitting frequent measurements of cardiac output without buildup of high indicator concentrations in blood, which can result in toxic responses or nonlinearity of detector performance.

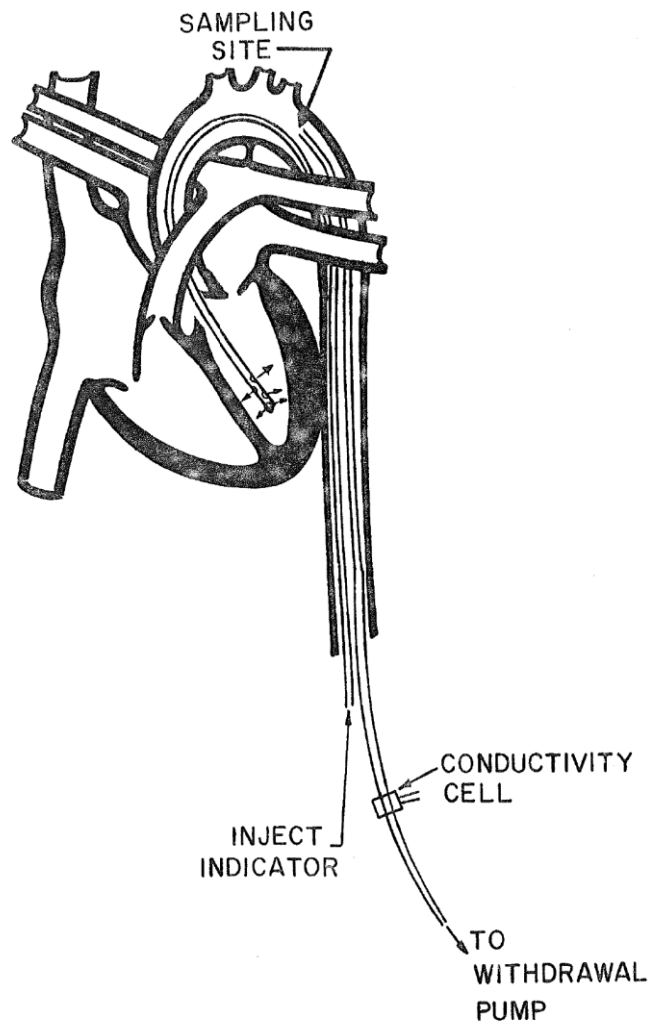


FIG. 1. Technique for measuring blood flow during CPR with ventricular fibrillation. The indicator (5% saline) is injected forcibly into the left ventricle. The multi-hole catheter aids mixing of indicator with blood. The dilution curve is inscribed by withdrawing aortic blood into an electrically calibrated conductivity cell.

The saline indicator is detected in blood withdrawn from the descending aorta through a 0.1 ml volume conductivity cell. The withdrawal rate is low with respect to cardiac output (e.g., 10 ml/min or less). The criterion used by the authors is a withdrawal rate of no more than 5% of cardiac output, even during conditions of low output during CPR. The conductivity cell can be calibrated electrically to provide a signal that is equal to a known concentration of saline in blood [1]. This feature eliminates the need for mixing calibration solutions. In a previous paper [1], it was shown that the change in concentration of saline in blood is given by the expression,

$$\Delta C = \frac{\Delta R \cdot \frac{A}{L}}{\frac{\Delta \rho}{\Delta c}},$$

where ΔC is the change in the concentration of saline in blood equivalent to a change in resistance (ΔR) introduced into the measuring circuit for calibration (e.g., 10 ohms), A/L is the ratio of area to length of the conductivity cell, and $\Delta \rho/\Delta c$ is the manner in which blood resistivity changes with the addition of saline. In dog blood at 37°C,

$$\frac{\Delta \rho}{\Delta c} = 3.77e^{0.48H},$$

where H is the packed cell volume in percent. The units for sodium chloride concentration are g/liter; R is in ohms, and resistivity, ρ , is in ohm-cm. Information on the derivation of this relationship and values for $\Delta \rho/\Delta c$ can be found elsewhere [2].

Essential requirements for valid use of the indicator dilution method are that the indicator enter a mixing pool through which all of the cardiac output flows and that uniform mixing occurs. In the method used in this study, this pool is the left ventricle. During CPR, the mechanical action of the heart is profoundly altered, and the investigator should be aware that the quality of mixing may not be adequate for use of the indicator dilution technique.

Here the quality of mixing was tested by vigorously injecting 2 ml of 5% saline into the left ventricle and obtaining dilution curves from two different arteries. Blood was simultaneously withdrawn through conductivity cells connected to catheters in the brachial artery and the femoral artery. During CPR with fibrillation, the two dilution curves provided cardiac output values that were within 10% of each other. Poor mixing would likely have produced dilution curves from the two sampling sites with different areas. Figure 2 illustrates the relationship between cardiac output determined from femoral and from brachial artery dilution curves in five dogs. Each data point represents one left ventricular injection of indicator.

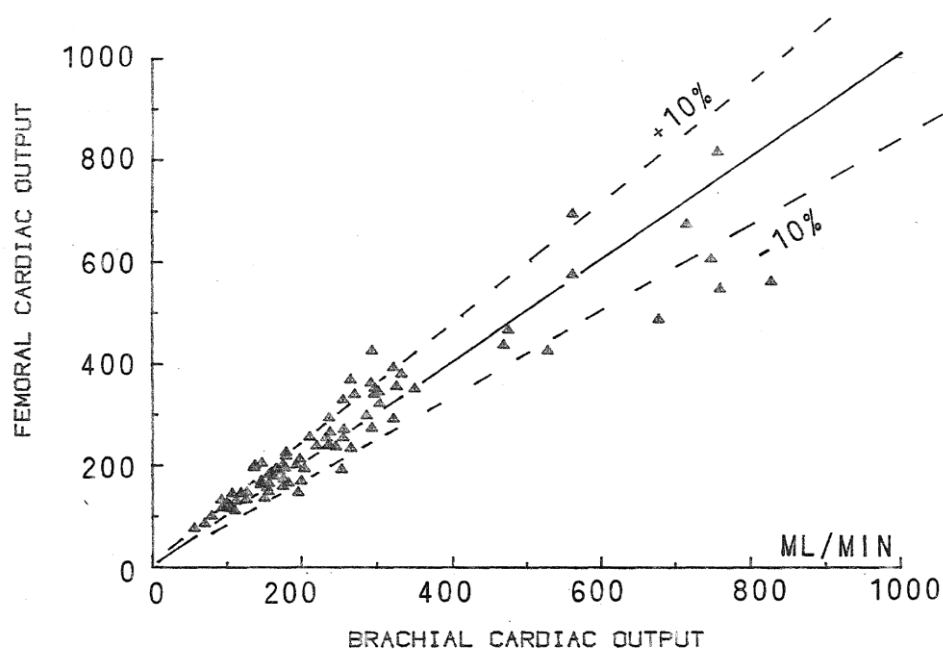


FIG. 2. *The relationship between cardiac output with ventricular fibrillation and CPR in dogs when computed from simultaneous femoral and brachial artery dilution curves.*

Figure 3 illustrates the type of dilution curve obtained with ventricular fibrillation and CPR. Ventricular fibrillation was precipitated in a dog and CPR was initiated with the Thumper[®] mechanical chest compressor and ventilator (Michigan Instruments, Grand Rapids, MI). Then the chart speed was reduced and 2 ml of 5% saline were injected into the left ventricle and the mixed sample was withdrawn from the aorta to inscribe the dilution curve. The electrical calibration signal (5 ohms) was equal to a concentration of 1.33 g/liter of saline in blood. The cardiac output was calculated to be 0.151 liter/min.

To further illustrate the practical advantage of this method, dilution curves were obtained using right-ventricular and left ventricular injection of saline during fibrillation with CPR in dogs. Right ventricular injection provided a poor quality dilution curve that was virtually impossible to process (Fig. 4a); whereas the left ventricular injection provided typical dilution curves essentially free from recirculation artifact (Fig. 4b). From a practical standpoint, it was found that cardiac output can be measured reproducibly with this technique for flow rates as low as 7 ml/min/kg.

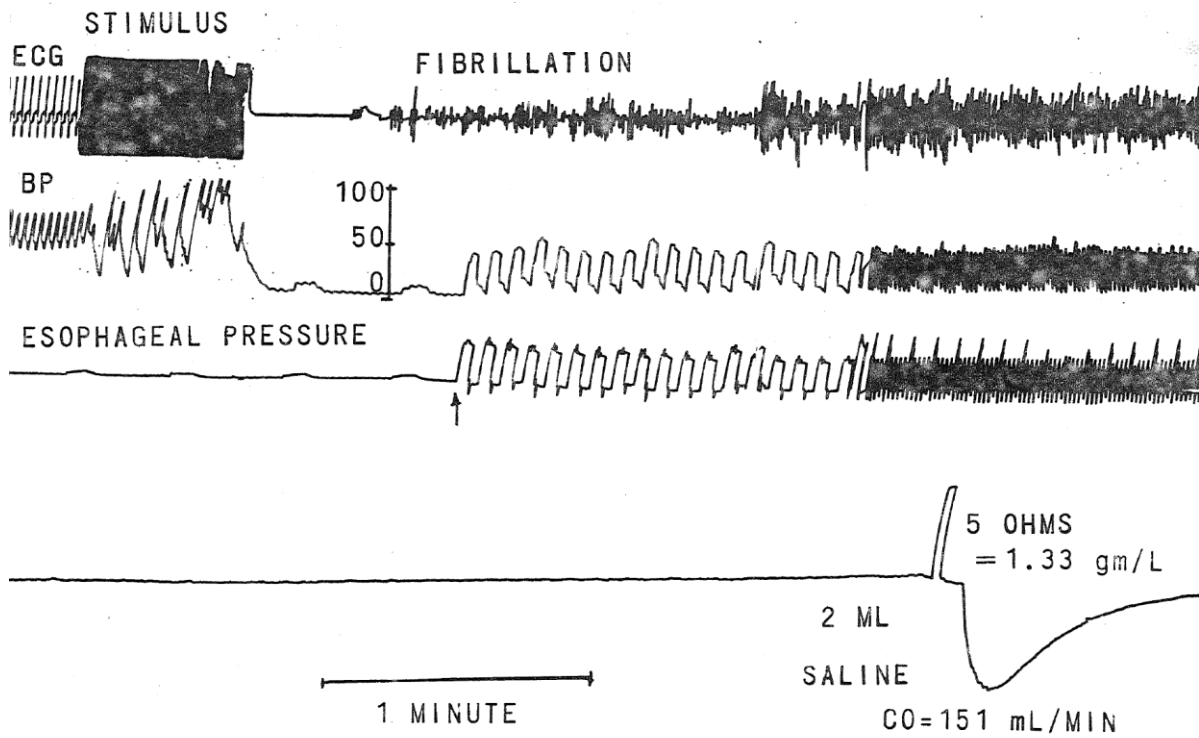


FIG. 3. The ECG, arterial blood pressure, and esophageal pressure in the dog before and after the induction of ventricular fibrillation in the dog. After CPR was provided by the Thumper[®] (arrow) 2 ml of 5% saline were injected into the left ventricle. The dilution curve was inscribed by withdrawing blood through the conductivity cell from the descending thoracic aorta. Cardiac output is calculated as the amount of indicator injected (grams), divided by the area of the dilution curve (minute-grams/ml).

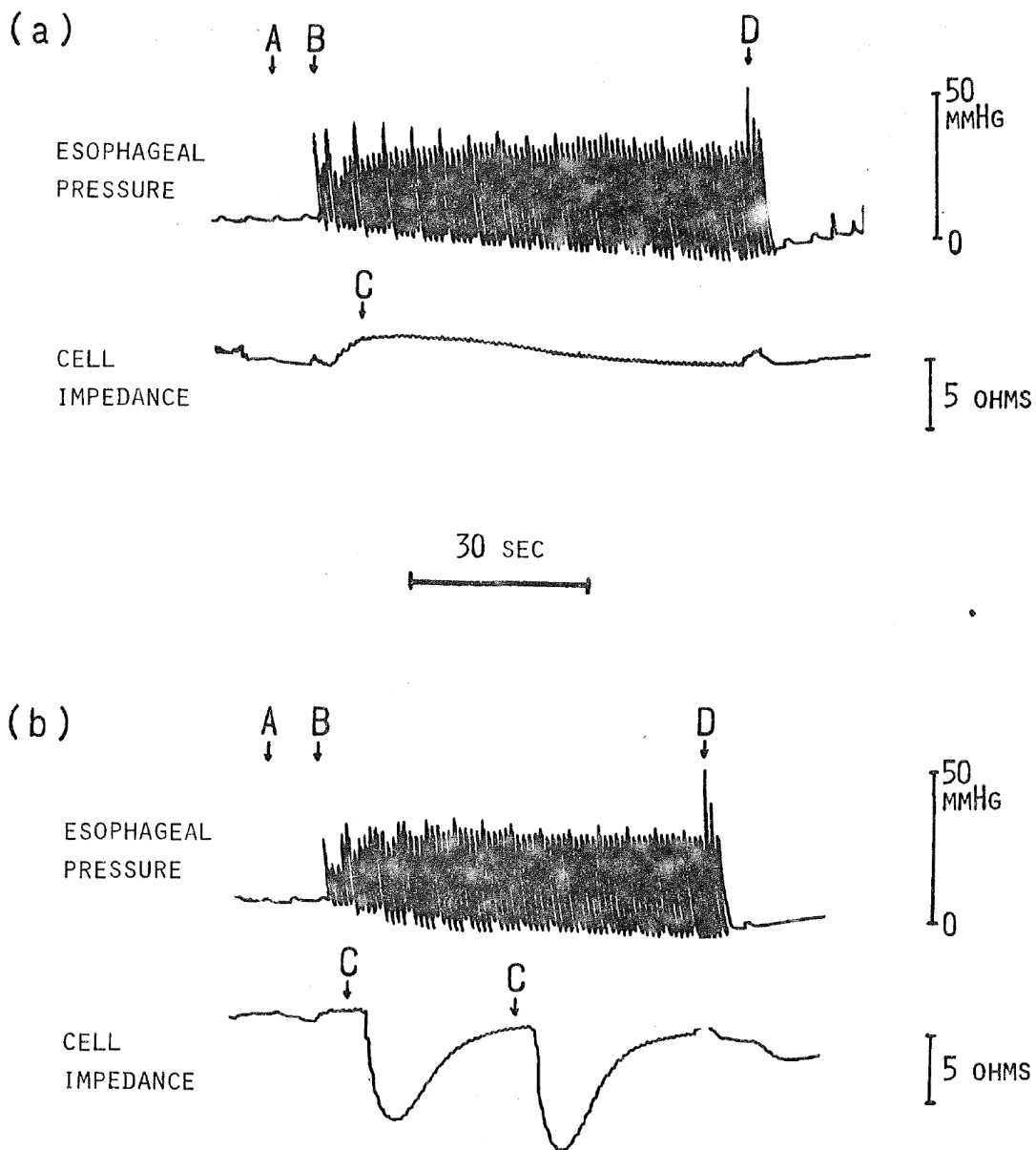


FIG. 4. Dilution curves obtained during experimental CPR in a 10-kg dog by (a) right ventricular and (b) left ventricular injection of saline indicator. Upper traces show intra-esophageal pressure, a reflection of chest compression. Lower traces show impedance of conductivity cell through which blood is drawn at 10 ml/min from the abdominal aorta. Passage of indicator causes cell impedance to decrease. A, fibrillation precipitated; B, chest compressions begun; C, indicator injected; D, defibrillation. The extremely poor quality dilution curve in (a) compares with the good quality dilution curves in (b).

DISCUSSION

Other techniques may be used to study flow and/or output: the classic Fick method using oxygen uptake, the dye and the thermal dilution methods, the injection of radioactive microspheres with surrogate organ withdrawal, or the estimation of change in output by monitoring arterial flow with an ultrasonic probe. All of these conventional techniques have limitations for measuring low cardiac output. Preliminary trials with the thermal method provided large errors due to heat loss to the vessels, rather than to the blood alone. Accordingly, the authors have endeavored to adapt the indicator dilution technique using saline to the very low output conditions of CPR. Improved dilution curve amplitude and appearance time were obtained using an injection-sampling scheme which may, in principle, compromise uniform mixing of indicator in blood. However, the authors were unable to demonstrate any obvious deterioration in the uniformity of mixing, and, therefore, conclude that this modified dilution technique is valid under conditions of CPR, provided indicator injection is done rapidly and a multi-side-hole catheter is used to promote mixing.

The studies employed by us to validate indicator mixing are in agreement with those carried out by others. For example, Sleeper et al. [3], using dye as an indicator injected into the superior vena cava, compared dilution curves obtained by brachial and femoral artery sampling in man. The two curves differed by less than 10% in area. The results of this study are also in agreement with those of Peterson et al. [4] who measured cardiac output in dogs by the rapid injection of dye into the left ventricle through a multi-hole catheter. Dilution curves recorded from the thoracic aorta and the femoral artery yielded cardiac output estimates with a coefficient of variation (SD/mean) of 10.5%.

In conclusion, the authors believe that the lesser opportunity for mixing occasioned by left ventricular versus right sided injection of indicator, and the absence of direct cardiac pumping action, do not produce significant deterioration in the quality of dilution curves inscribed during CPR by the method that has been developed. The authors, therefore, believe that this method is a valuable tool for future studies of the physiology of blood flow during CPR in animals.

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