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A Flexible Scintillation Probe for Cardiac Output Determination

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The determination of the amount of blood pumped by the heart per unit time (cardiac output) is an important physiological parameter. In principle, cardiac output can be measured by cannulating all the veins returning to the heart or by cannulating the pulmonary artery. However, such a direct approach exhibits obvious difficulties and several methods have been devised for measuring cardiac output by indirect means, the two most commonly employed being the Fick method and the Stewart-Hamilton method.

The Fick method determines the pulmonary blood flow by measuring the consumed oxygen and the arterio-venous oxygen difference in blood samples. This method requires cardiac catheterization and complex equipment and does not lend itself to repeated trials.

The Stewart-Hamilton method (1, 2) is based on the measurement of the dilution of an injected dye, such as Evans blue, or of a radioactive isotope. Arterial blood is monitored to determine the time-concentration curve of the tracer. The need of arterial puncture makes this method undesirable.

A modification of the Stewart-Hamilton method (3-10) employs an external radiation detector to determine the dilution of a radioactive substance introduced into the heart. While this method requires intravenous injection of the tracer, it exhibits the advantage over the conventional Stewart-Hamilton method in that it does not require arterial puncture. However, because the external monitoring sites are relatively distant from the region of interest the time dilution curve is often distorted by other components of the circulating radioisotope. Furthermore, positioning of the detector has been reported to be very critical (11).

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In an attempt to minimize the drawbacks of the previous method a new approach has been developed utilizing the esophagus as a pathway for positioning a small scintillation detector opposite the aorta (Fig. 1). The close proximity of the aorta to a collimated detector placed in the esophagus reduces the influence of other pools of tagged blood (Fig. 2). In addition, this monitoring site yields primary dilution curves with steep descending slopes enabling them to be easily delineated from the effects of recirculation (Fig. 3).

APPARATUS

The apparatus used in this study is a scintillation probe the detector of which is a thallium activated cesium iodide cylindrical crystal approximately 3 mm in diameter and 5 mm long. The crystal is optically coupled to an end-window photomultiplier tube by a flexible fiber optics light guide (Fig. 4). Cesium iodide was selected as the phosphor because of its high photon absorption efficiency, its quality as a phosphor, and because it is not hydroscopic. The crystal detector is shielded by a tantalum enclosure in which is provided a small rectangular aperture (3 mm × 5 mm) (Fig. 5)[1]. A one mil aluminum covering over the window insures a moisture-proof and light-tight compartment. The shield thickness is approximately 1.2 mm providing a 100-fold attenuation for the 140 keV radiation emitted by technetium-99m which was used in these studies.

The fiber optics light guide which connects the detector to the photomultiplier tube is 60 cm in length and about 3.3 mm in diameter. It is composed

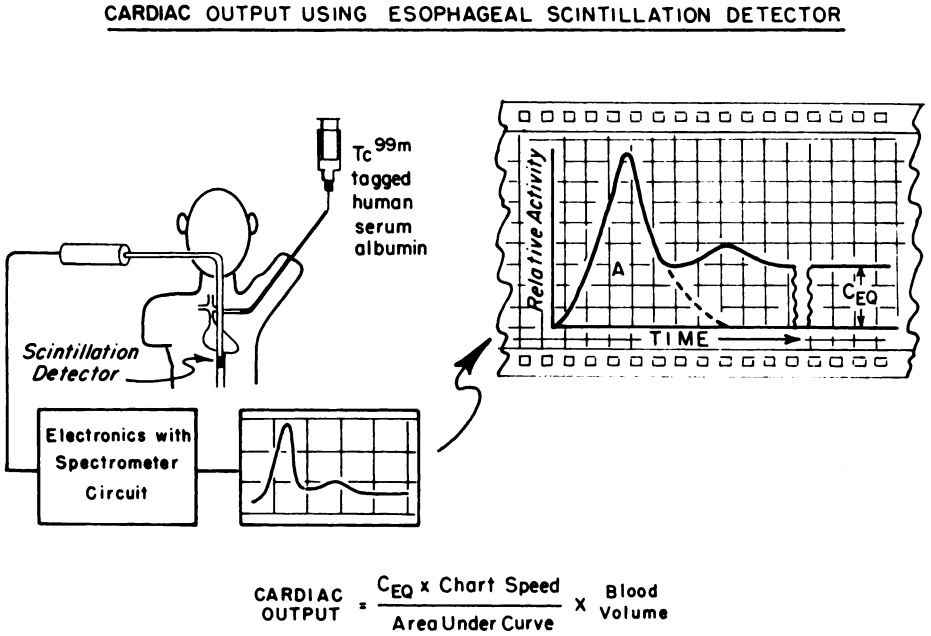

Fig. 1. Cardiac output using esophageal scintillation detector.

of noncoherent glass fibers 75 microns in diameter. The fluorescence of the light guide when exposed to ionizing radiation is low and it has been found to be negligible in the present application. The light guide is flexible and not affected by routine handling and usage. The flexible probe can be cold sterilized by immersion.

The end-window tube used is a XP1110 photomultiplier manufactured by Amperex. The physical dimensions of the tube are 19 mm in diameter and 10 cm in length.

The efficiency of this probe for the detection of the electromagnetic radiation emitted by Tc-99m was measured to be in excess of 10%.

METHOD

The general criteria in the selection of a substance suitable for determining the cardiac output by the dilution principle with the above described probe are:

1) The injected substances must exhibit low toxicity.

2) The radioactive label should have properties which minimize the dose of radiation delivered to the patient examined.

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[1]Probes of various diameters were tested in this study. The probe shown in Fig. 3 is typical of the most recent design used.

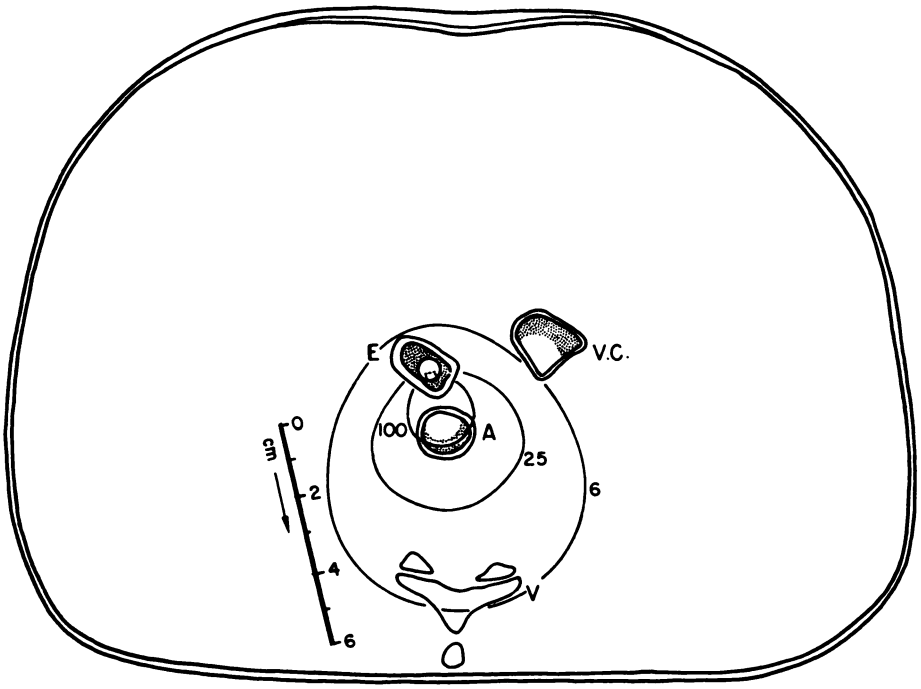

Fig. 2. Scale diagram of horizontal chest section showing iso-response curves of the probe for Tc-99m. The iso-response curves were determined in water using 0.5 ml of Tc-99m.

3) The activity must remain in the blood stream for a period of time long with respect to the measurement. (See next section.)

4) The energy of the ionizing radiation emitted by the radioactive tag must be high enough to penetrate tissue with little attenuation, but it should also be low enough to insure efficient detection and adequate shielding by a small amount of material surrounding the scintillation crystal.

It was found that human serum albumin tagged with technetium-99m fulfilled adequately the above criteria. Injected serum albumin remains reasonably well confined to the blood pool for a period of time long with respect to the measurement. It is nontoxic. The short physical half-life of Tc-99m (6 hrs), its minimal particle emission and the energy of its gamma radiation fulfill suitably the conditions imposed upon the radioactive tracer. It was found that the administration of approximately 300 μc of Tc-99m labeled serum albumin is an adequate dose to measure accurately the cardiac output in an average patient. The dose of radiation delivered to the patient under such conditions compared with a more conventional procedure is shown in Table I.

An idealized curve of the activity recorded by the esophageal probe following intravenous injection of tagged serum albumin is shown in Figure 1. The arterial concentration rises rapidly as the bolus passes the detector and then falls off. The smooth downward slope is interrupted by a shallow second peak which represents the recirculation of some of the tagged blood. The level of the activity gradually reaches a constant value when the tagged serum albumin has been uniformly distributed throughout the blood. A blood sample is withdrawn at this time. To evaluate the subject's cardiac output three factors must be determined:

1) The area of the primary curve which represents the activity detected during the transit of the bolus past the detector. Since mixing has occurred in the chambers of the heart the descending slope of the primary peak will be an

TABLE I

COMPARISON OF TC-99M AND I-131 LABELED SERUM ALBUMIN FOR CARDIAC OUTPUT DETERMINATION

Radio-Pharm.	*Activity Administered*	*Physical Half-Life*	*Organ Absorbed Dose*	*Estimate (mrads) (17) Dose*
Tc-99m albumin	300 μc	6 hrs.	Total Body	5
			Blood	14
I-131 albumin	5 μc	8.1 days	Total Body	5
			Blood	87

exponential function of time and must be separated from the effect of recirculation. This is accomplished by extrapolating a semi-logarithmic plot of the descending slope and replotting the original curve to zero activity. The area of the primary peak thus delineated can be measured by means of a planimeter. (This area can also be evaluated quickly by appropriate formulas (12-15)).

2) The equilibrium activity at the time of the withdrawal of the sample is measured. In general, an elapsed time of ten minutes after injection is sufficient to insure complete mixing. If any of the tagged material has been removed from the blood its loss may be compensated by evaluating the equilibrium value and withdrawing the blood at the same time.

3) The subject's blood volume is determined by the dilution technique by comparing the amount of activity injected to the amount of activity per unit volume of the blood withdrawn at equilibrium.

The cardiac output can be determined on the basis of the above factors as follows:

$$\text{Cardiac Output} = \frac{C_{eq} \times \text{Chart Speed}}{\text{Area under curve}} \times \text{Blood Volume.}$$

If C_{eq} is measured in inches, the area in square inches, the chart speed in inches per min., and the blood volume in liters, this equation gives the cardiac

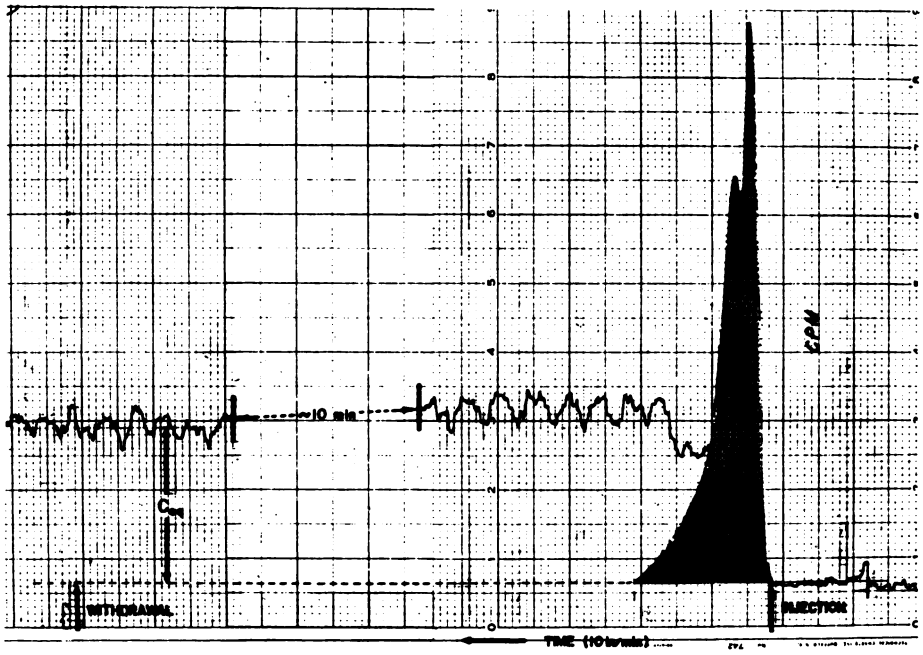

Fig. 3. Radioactivity vs. time concentration curve determined by means of the probe showing extrapolation of the descending slope.

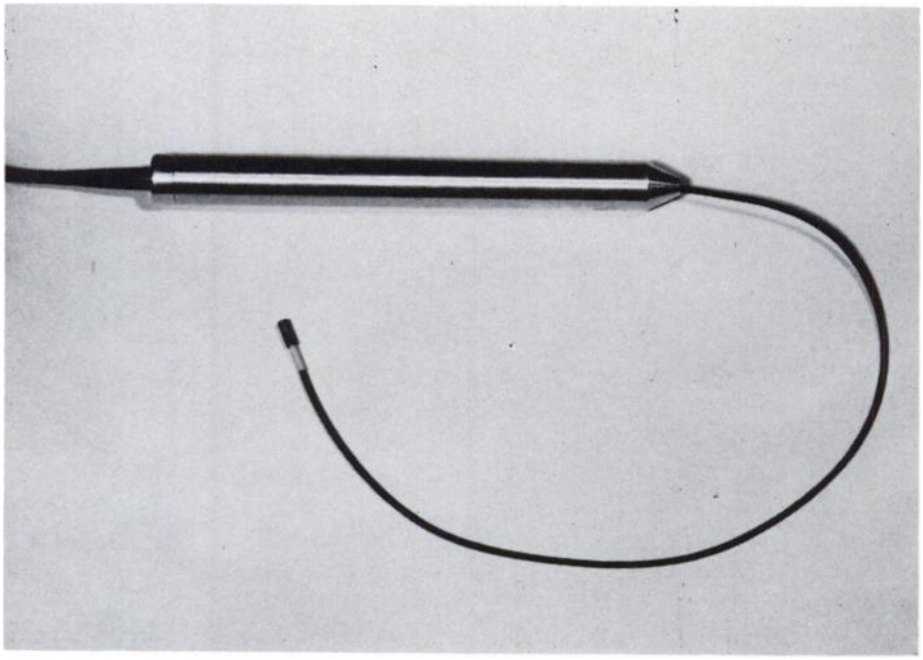

Fig. 4. Flexible scintillation probe and photomultiplier housing.

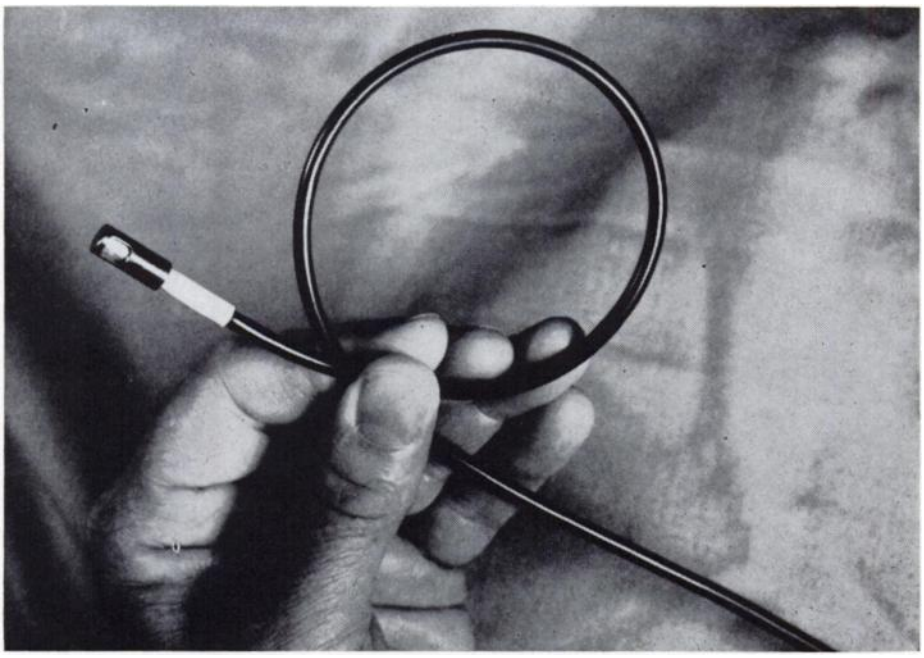

Fig. 5. View of probe showing the tantalum shield and the window and demonstrating the flexibility of the light guide.

output in liters per minute. If repeated measurements of the cardiac output are to be performed in a short interval of time during which it may be assumed that the blood volume remains constant the changes in cardiac output can be determined by the changes in the ratio of the equilibrium activity and the area under the curve providing the chart speed is unchanged and a new baseline is established.

DISCUSSION

The validity and the reproducibility of the above described method were ascertained in two ways: (1) The cardiac output of a series of dogs were determined simultaneously with the esophageal probe and the dye dilution method employing cardio-green. In this experiment the technetium-tagged serum albumin was mixed with cardio-green and injected by means of a catheter into the right heart. Correlation of the two methods for a series of 20 trials was found to be good (16). While this method establishes a correlation between the described method and the dye dilution method it does not establish the validity of

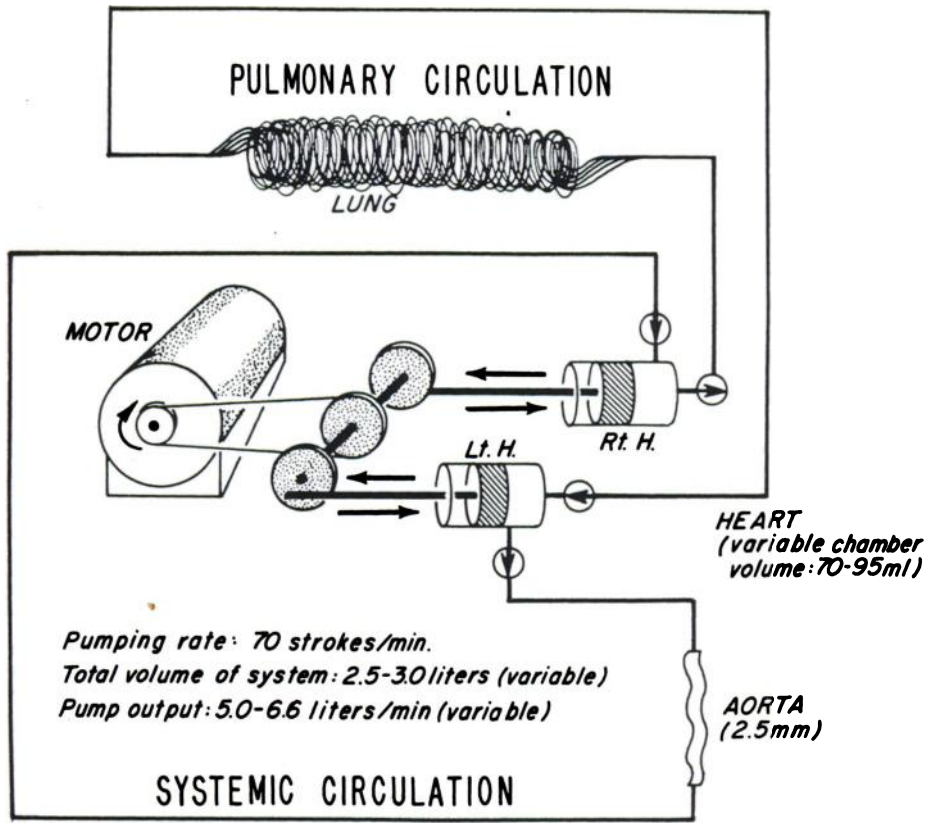

Fig. 6. Block diagram of the model of a human cardio-vascular system used for testing the validity of the described method in measuring cardiac output.

the use of the esophageal probe on an absolute basis. A model circulation system simulating the human circulation system was designed and built to test directly the validity of the use of the probe (Fig. 6). Test determinations of the output of the model performed with the esophageal probe placed in close proximity to the "aorta" of the model agreed remarkably well with the known pumping rate. It should be noted that in the latter test the activity was injected into the "right" or "left" heart.

SUMMARY

It appears that the use of a flexible esophageal scintillation probe provides a useful instrument for the determination of the cardiac output in patients by means of the injection of radioactive serum albumin. The probe in its present form is easy to introduce into the esophagus of an adult or of a child older than about 5-6 years.

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