A Comparison of Cardiac Output Determined by the Fick Procedure and a Direct Method Using the Rotameter

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Experiments were performed on the anesthetized dog to determine the accuracy of the widely used Fick procedure. Cardiac output values, recorded by an optical rotameter, served as a reliable standard for comparison. Under the conditions of these experiments, comparisons showed excellent agreement. The average variation between the two series of the measurements was ±8 per cent. Twelve of thirteen comparisons agreed within less than ±8 per cent. This small deviation was within the range of error which might have existed on the basis of known technical inaccuracies.

The FICK procedure has gained acceptance as one of the most reliable of the many technics for quantitating cardiac output. The accuracy of most other methods has been established by comparison with it, and since the advent of right heart catheterization it has become an important tool in clinical research. Such reliance, however, as has been placed upon the Fick procedure does not seem wholly justified, since it is an indirect method and has never been satisfactorily checked against a standard of established accuracy. Data from the experiments of Bohr and Henriques 1 in 1897 show that in dogs the Fick method gives values far too high when compared with a direct technic (stomuhr in the aorta). While these experiments are undoubtedly crude by present day standards, they have never been repeated; and the absolute accuracy of the Fick method has remained a question. Accordingly, in the present investigation, experiments were performed in the anesthetized dog in which the cardiac output was determined simultaneously by the Fick procedure and an optical rotameter method. The rotameter could be safely used as a standard of reference, since it has been shown that this device measures blood flow directly with a high degree of accuracy.

Methods

Flow measurements were made simultaneously by the Fick procedure and rotameter over a six-minute period in open-chest dogs which were anesthetized with Nembutal (20–30 mg. per Kg., intravenously) or barbital (200 mg. per Kg., intravenously) following morphine (30 mg.).

For the Fick procedure, oxygen consumption was measured with a Benedict-Roth metabolism apparatus (Collins), which was modified for use in open-chest dogs after the plan of Harris and Matlock 2 (see Fig. 1). To improve the accuracy with which the oxygen slope could be read, the sensitivity of the apparatus was increased by means of a pulley system so that 1.0 mm. deflection equaled 8.33 cc. A rubber catheter was inserted through a tracheal incision and tied securely, and the spirometer containing 100 per cent oxygen was attached to the catheter ten minutes or more before a test period began. To test for leaks, at the end of each experiment the apparatus was run for four to six minutes with the dead dog in the circuit.

Arterial blood samples were obtained by puncturing a rubber vial cap which sealed the vertical limb of a glass T-tube in the carotid artery. Mixed venous samples were taken directly from the outflow side of the rotameter which measured flow through the pulmonary artery. Samples were drawn manually in oiled syringes containing enough heparin to fill the terminal dead space. They were taken simultaneously and continuously at 1.0 cc. per minute during the six minutes in which oxygen consumption was measured. Immediately after withdrawal, the syringes were capped and placed in ice water, and within two to three hours the oxygen content of each sample was determined in duplicate by the nomographic method of Van Slyke and Neill. 3 Blood from each dog was also analyzed for oxygen capacity.

As a standard of reference for the Fick procedure, the cardiac output was determined directly by measuring blood flow through the pulmonary artery with an optical rotameter. This method, described in a previous communication, 4 avoids the error inherent in other direct procedures which fail to measure coronary flow (flow meters in aorta and vena cavae). Briefly, the pulmonary artery was exposed, dissected free, and a specially devised cannula was inserted into the artery. During cannulation, hemorrhage was avoided by diverting the flow through a
temporary shunt or by a fibrillation-defibrillation technic which permitted a temporary cessation of the circulation. After insertion of the cannula, the rotameter was attached to it. The output of the right heart then passed from the pulmonary artery through the rotameter and was distributed to the right and left lungs. This circuit permitted continuous optical recording of total cardiac output. Heparin (10 mg./Kg.) was used as an anticoagulant with the rotameter. In order to obtain different levels of flow, varying amounts of blood (50-200 cc.) and/or epinephrine (1:5000 or 1:10,000) were administered intravenously during some of the test periods. After each experiment, the rotameter was calibrated with the dog’s own blood. Mean flow for each minute was calculated by planimetric integration of the area under the recorded flow curve, and the average flow per minute for the six-minute test period was compared with that obtained by the Fick procedure.

In addition, early in this investigation, several experiments were performed in which cardiac output determined by the Fick procedure was compared with right heart input, determined by the method of Gregg and Shipley. Blood was collected from the vena cavae and after passage through a rotameter that mixed venous samples were obtained from a catheter placed in the pulmonary artery.* Combining the Fick procedure with direct technics proved difficult, and the number of successful experi-

* In both open and closed-chest experiments, venous samples were obtained from the pulmonary artery, which site has been shown to be optimal in dogs for complete mixing.† Data collected in the preparatory stages of the present work confirmed this fact. In one typical experiment, four samples drawn simultaneously by catheters from the right ventricle, conus, and two sites in the left pulmonary artery showed oxygen contents, respectively, of 9.42, 9.63, 9.72, and 9.72 volumes per cent.

Fig. 1.—Diagram of basal metabolism apparatus used as spirometer and artificial respirator. Tank T is added to enclose spirometer bell. Positive pressure delivered intermittently to T inflates lungs, deflation occurring when pressure is dissipated through regulated leak valve. Bell is undercounterbalanced to assist deflation. External system replaces inside flutter valves.
ments was, therefore, limited. Of thirty-three experiments begun, eighteen were completed. Of these, eight were discarded because leaks in the spirometer system could be demonstrated or duplicate blood oxygen content determinations did not check closely enough. The remainder, thirteen comparisons in 10 dogs, forms the basis for this report.

The results of these experiments are presented in Table 1. Examination of the data discloses that the Fick procedure was tested under a variety of conditions. Oxygen consumption varied from 21-94 cc. per minute; arteriovenous differences from 2.01 to 12.40 volumes per cent, flows from 668-1463 cc. per minute, and mean blood pressure from 63-160 mm. Hg. In the table, comparisons of the Fick procedure with the direct methods are expressed as per cent deviation of the former from the latter. The average variation between the two series of measurements is ±5 per cent. It can be seen that eight of the thirteen comparisons agree within 3 per cent, twelve of the thirteen within ±8 per cent. The greatest deviation, and the only one of this magnitude (+17 per cent) observed in Experiment 5, probably reflects inordinately large technical errors resulting from a small oxygen consumption, and very low arteriovenous difference.

The cardiac output during these experiments was both constant and variable. During eleven of the test periods, the flow and mean blood pressure remained essentially constant. Repre-

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Table 1.—Comparison of Cardiac Output by Fick and Rotameter Methods

| Experiment | Weight | Mean B. P. | Fick
<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
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<td>Kg. mm. Hg cc./min.</td>
</tr>
<tr>
<td>1. (2/21/49)</td>
<td>10.2</td>
<td>78 83.4 21.31</td>
<td>20.47 8.11 12.40 672</td>
</tr>
<tr>
<td>2. (2/23/49)</td>
<td>10</td>
<td>85 78 19.25</td>
<td>15.84 7.66 8.17 955</td>
</tr>
<tr>
<td>3. (2/24/49)</td>
<td>9.5</td>
<td>83 63.2 10.68</td>
<td>11.22 6.85 4.38 1443</td>
</tr>
<tr>
<td>4. (8/30/49)</td>
<td>11</td>
<td>92 84 —</td>
<td>15.29 8.09 7.31 1110</td>
</tr>
<tr>
<td>5. (9/1/49)</td>
<td>12</td>
<td>123 21 18.22</td>
<td>15.58 13.62 2.01 1045</td>
</tr>
<tr>
<td>6. (10/12/49)</td>
<td>—</td>
<td>95 77 16.75</td>
<td>15.70 7.84 7.83 984</td>
</tr>
<tr>
<td>7. (11/8/49)</td>
<td>15</td>
<td>95 94 22.00</td>
<td>15.58 7.79 16.05 8.92 7.14 1132</td>
</tr>
<tr>
<td>8. (11/15/49)</td>
<td>12</td>
<td>87 82 23.32</td>
<td>15.60 12.02 19.66 12.10 7.62 1080</td>
</tr>
<tr>
<td>10. (12/2/49)</td>
<td>13.5</td>
<td>90 89 17.56</td>
<td>15.60 6.38 9.19 970</td>
</tr>
</tbody>
</table>

Average

|        | 75 | 7.78 1007 994 | ±5 |

* Experiments 1, 2, 3, closed chest-caval technic, 5 per cent added to rotameter values for coronary flow according to the data of Eckenhoff and co-workers. * Adjusted figures are in parentheses. Experiments 4-10, open chest-pulmonary artery technic. Mean carotid blood pressure was recorded optically with the Gregg manometer.

Results

The results of these experiments are presented in Table 1. Examination of the data discloses that the Fick procedure was tested under a variety of conditions. Oxygen consumption varied from 21-94 cc. per minute; arteriovenous differences from 2.01 to 12.40 volumes per cent, flows from 668-1463 cc. per minute, and mean blood pressure from 63-160 mm. Hg. In the table, comparisons of the Fick procedure with the direct methods are expressed as per cent deviation of the former from the latter. The average variation between the two series of measurements is ±5 per cent. It can be seen that eight of the thirteen comparisons agree within 3 per cent, twelve of the thirteen within ±8 per cent. The greatest deviation, and the only one of this magnitude (+17 per cent) observed in Experiment 5, probably reflects inordinately large technical errors resulting from a small oxygen consumption, and very low arteriovenous difference.

The cardiac output during these experiments was both constant and variable. During eleven of the test periods, the flow and mean blood pressure remained essentially constant. Repre-
sentative rotameter curves from such experiments are shown in figure 2. Respiratory varia-
parative results was noted. This might be ex-
lpected, since these deviations about the mean

tions in flow, as seen in these records, occurred in all experiments. Although the magnitude of these variations differed, no influence on com-
are regular and relatively small. With constant flow, the rate of oxygen consumption was even and the resulting linearity of the oxygen slopes,
as shown in figure 2, improved the accuracy with which oxygen uptake could be measured.

Sizeable irregularities in flow resulted from an uneven infusion rate in two experiments (table 1: 4a and 6b). Although the cardiac output varied ±30–40 per cent for at least one-half the test period, the agreement of the two methods in these instances does not appear to be affected. Figure 3 shows sections of records from these experiments.

Fig. 3.—Flow curves from open-chest dogs with variable cardiac output and mean blood pressure. Time, 6 seconds.

Discussion

Under the condition of these experiments, the Fick method accurately measured the average minute output of the heart. During the majority of the determinations, the output remained constant, but in two experiments with considerable variation in flow, good agreement was also noted. This is not surprising; for the Fick equation should remain valid with variable flow, if an average oxygen uptake and arteriovenous difference is obtainable with the technics used. Naturally, this demands continuous blood sampling over the entire period that oxygen uptake is being measured.

The small scatter of results which does persist in this work may be explained when known technical errors in the Fick and direct methods are considered.

The comparisons with the least technical error are those in which direct measurements of output were made in the pulmonary artery. In the Fick procedure, the error in measuring oxygen uptake, in the absence of leaks, is determined by the accuracy with which the oxygen slope can be read, and approximates 5 per cent. The error in determining the arteriovenous difference may be judged by noting the average difference of duplicate blood oxygen analyses which is 0.033 volumes per cent for the twenty-six pairs in table 1 (only one pair of samples differs more than 0.08 volumes per cent). A glance at the table shows that such differences cannot introduce an error of more than 1 or 2 per cent in the Fick method. The error introduced by the rotameter in these comparisons is also small. With the use of a pump system, we were able to show that this instrument measures flow within ±3 per cent, and this is not significantly altered by changes in viscosity or flow pattern over a wide range.
COMPARISON OF CARDIAC OUTPUT DETERMINATION

Therefore, when the estimated errors in the two methods are considered, the probable deviation which may occur on a technical basis approximates \( \pm 10 \) per cent.

In the three comparisons in which vena caval flow values served as the standard of reference, the error in the Fick procedure is the same as outlined above. The error in the rotameter method is increased somewhat, since a value for coronary flow can only be approximated. The results of these comparisons are within the same range as those using the more accurate pulmonary artery technic. The data from these experiments has been included in this report, since it supplies additional information on the accuracy of the Fick method in closed-chest dogs with spontaneous respiration.

Although this work was performed on operated animals, there is no reason to believe that the accuracy which has been demonstrated for the Fick method will be altered in the unanesthetized dog, provided that technical errors do not exceed those in the present work.

## Summary

When the Fick procedure was compared with a direct method of high accuracy, excellent agreement was observed in a variety of hemodynamic states. Twelve of thirteen comparisons in the present work agreed within less than \( \pm 8 \) per cent. This was within the range of error which could exist on the basis of known technical inaccuracies.

## Addendum

Since this manuscript was submitted, Huggins and others, Am. J. Physiol. 160: 183, 1950, have compared cardiac input measured by the rotameter with output by the Fick procedure, the latter serving as the reference method. These comparisons, which range from \( +26 \) to \(-29 \) per cent, are not believed to serve as a measure of the accuracy of either method since (1) the rotameter did not measure coronary flow and thus underestimated total cardiac input; (2) the venous sample in the Fick procedure did not include coronary venous blood and thus caused an overestimation of total cardiac output; (3) the method of Roughton and Scholander for blood \( O_2 \) content is less accurate than the Van Slyke technic and its use therefore increased the probable error in the determination of the \( O_2 \) A-V difference. The vagaries noted by Huggins in the operation of the rotameter per se, do not occur if the line voltage is kept constant, the blood is properly filtered before calibration, and the calibration is made at the temperature and viscosity existing at the time of flow measurement. Under these conditions, rotameter calibration curves in our series are found to vary no more than 3 per cent from day to day.

## Acknowledgments

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