Studies Made by Simulating Systole at Necropsy


With a Note on the Diminution of Heart Work as Age Advances

By Isaac Starr, M.D., S. I. Askovitz, M.D., W. Feder, M.D. and A. Schild, Ph.D.

"Left ventricular" work can be estimated with great accuracy in cadaver experiments in which both pressure curves and curves of cardiac output at each instant of systole were recorded. Using these accurate estimates as a target, methods have been sought which would permit the estimation of cardiac work from measurements which could be made in the clinic and the accuracy of such methods has been assessed. A method of approximating the left ventricular work has been devised which is so simple that it could be used by any doctor practicing medicine.

There can scarcely be any doubt that knowledge of the heart's work is the most important single aspect of any quantitative assessment of cardiac function and that if one could estimate heart work with reasonable accuracy, it would lead to a better understanding of heart disease. Cardiac output is of importance because it is the concern of the rest of the body, but noncardiac factors, such as changes in vascular resistance, greatly influence the relation of cardiac work to output. The senior author's interest in this problem has extended for many years; indeed, his long concern with cardiac output methods has stemmed largely from the fact that such results would permit rough estimations of cardiac work.

Most textbooks of physiology discuss the heart's work, but this aspect of cardiac performance has received little attention in the clinical literature, doubtless because methods of estimating it, well suited to the clinic, have not been available. This study aims to provide such methods.

Indeed, the formula most frequently employed by physiologists for estimating cardiac work gives only an approximation of the true value. It is as follows:

\[ \text{Work} = QR + \frac{Mv^2}{2g} \]  

(a)

Where \( Q \) = volume of blood expelled from the heart per beat, \( R \) = resistance, usually expressed as mean blood pressure in mm. Hg \( \times 13.6 \), \( v \) = velocity of blood at the root of the aorta, \( M \) = mass of blood, and \( g \) = acceleration due to gravity. The second term on the right side of equation (a) represents the work done in imparting velocity to the blood, and \( M \) is usually taken as the cardiac output in cc. times the specific gravity of blood. In resting subjects this term represents so small an amount of the total cardiac work performed that it is usually neglected. In our old studies, it seldom exceeded 2 per cent of total work. Additional terms have been suggested for cardiac work equations, but of small magnitude and often difficult or impossible to estimate, these have been usually neglected also.

It has long been realized that the calculation of work from cardiac output and mean blood pressure by formula (a) might involve large errors. The main error is involved in the assumption that the output and pressure can

From the Department of Therapeutic Research of the Medical School of the University of Pennsylvania, Philadelphia, Pa.

This work was supported by research grant 625 C (1 to 5) from the National Heart Institute of the National Institutes of Health, United States Public Health Service.

1005 Circulation, Volume XII, December, 1955
be multiplied together without regard to time. To secure a correct estimate of work, the flow at every instant must be multiplied by the resistance at that instant, and the curve of cardiac ejection, instant by instant, has seldom been recorded. In hearts with a single ventricle, such as in the frog and turtle, the measurement has been made. Many years ago Otto Frank obtained such curves for the isolated frog heart and estimated work by this means. Later Katz secured similar curves by enclosing the isolated turtle heart in a volume recorder, and he also estimated work. But similar estimates of work are much more difficult to secure from mammalian hearts beating in situ, for volume recorders then contain both ventricles and so record the sum of the outputs of both at each instant, and this value cannot be used with the pressure in either pulmonary artery or aorta at the same instant, in a calculation of work, without introducing errors which might be large.

In a series of experiments performed on fresh cadavers in this laboratory by Starr, Schnabel and Mayock, systole was simulated at necropsy. From two of the records obtained, the cardiac ejection curve and central blood pressure, it was possible to estimate the work of each "systole" as work was defined by Newton, by multiplying pressure and the differential of volume instant by instant and taking the integral of the result, a method which we have no hesitation in claiming to be far more accurate than any which can be applied to living man or mammals. Also, the same two curves gave us data from which work could be estimated in the usual way, by formula (a).

The remaining two curves of our records, peripheral blood pressure and the ballistocardiogram, provided measurements of a type which could be made on any patient in the clinic. Therefore, with the accurate values of work estimated from the first two curves as a target, we have sought the best means of estimating left ventricular work from measurements that could be made by doctors working in the clinic. The mathematical analysis of the data required for this purpose was undertaken by the three younger collaborators of this paper who were well fitted both by training and inclination to carry out this difficult and exacting task. Dr. Askovitz acted as advisor and coordinator of this part of our work.

The principle underlying the mathematics which will determine the best method, defined as that method in which the sum of the squares of the errors is at a minimum, has long been known; and such computations, formerly of only limited value to medical investigators because they were so laborious to carry out, have become an important tool in medical research since the development of the electric computing machines. Thus, although the details of our mathematical methods may not be understood by many doctors, both the aim and the result can be readily comprehended by everyone. We aimed to produce a clinical method of estimating the work of the heart, a method of reasonable accuracy and of such simplicity that it could be used by any doctor practicing medicine, and we believe that we have come close to this goal.

Finally, after devising a simple method for estimating left ventricular work from blood pressure, we have estimated such work from published data on the average blood pressure of large groups of the population, and so determined the changes in the average heart work of healthy persons as age advances. The results show clearly that, as age advances, the average work performed by the heart at each beat diminishes markedly, and at the age of 60 the average cardiac stroke work is about two-thirds of that at 20 years.

**Material and Methods**

The physical characteristics and necropsy findings of the cadavers used have already been reported and the method of simulating systole has been described in detail. The experiments themselves were performed by Starr, Schnabel and Mayock. In brief, large cannulas were placed in the aorta and pulmonary artery and, after a diastolic pressure had been imparted by perfusion into a femoral artery, systole was simulated by injecting into these large arteries from syringes, the position of the pistons of these syringes being recorded continuously by an optical system. The record
consisted of four curves recorded simultaneously; the cardiac ejection curve, curves of blood pressure in the aortic arch and femoral artery, and the ballistocardiogram. These records were carefully tested for alignment. Examples have been illustrated in previous publications.5, 6

Such records were obtained from two groups of experiments, those in which the cadavers were perfused with blood and those in which they were perfused with water. The former group comprised 53 “systoles” in six cadavers. These experiments most closely reproduced conditions occurring during life and they were performed at the end of our long series, after our technique had been brought to its highest point. Therefore, in this presentation, the chief emphasis will be placed on the data secured from these experiments, although we shall also refer to results secured on a sample of 63 “systoles” secured in six cadavers perfused with water. The physical characteristics and the necropsy findings in this latter group have also been published.7 One subject, P. L., occurs in both groups having been perfused with water in some “systoles”, with blood in others.

**Cardiac Work Estimates:** Before designing our attack on the work of the heart, we had a philosophical problem to consider, for we must define our target. We must ask ourselves what the heart’s work consists of, and how this was to be expressed to yield values of the greatest usefulness. We do not regard this question as closed.

The senior author has long been interested in the problem of the mathematic expression of muscular work8 and he believes that there are many advantages in expressing it as the integral of the product of mass and acceleration, the latter measured with the acceleration due to gravity as base line. Cardiac work could be expressed this way also. However, the chief advantage of the newer system is that static and dynamic work are measured in similar terms, and the heart’s work is altogether dynamic as the pressure load during diastole is taken off the heart muscle by the valves. So the advantage of the new system, as an expression of cardiac work, would be problematic, and also, in order to apply it, our cardiac ejection curves would have to be differentiated a second time and this would markedly increase the error of the estimate. For these reasons, we have contented ourselves with the classic Newtonian method of expressing cardiac work in this paper, and we will use those values as our target.

The task of estimating Newtonian work by integration of the 53 curves secured on “systoles” produced by injections of blood, was undertaken by Dr. Feder. As a first step in these estimates, the “cardiac” ejection and aortic pressure curves were enlarged by means of a pantograph and then measured. From these measurements, work was estimated, the theory underlying the procedure being as follows:

The concept of work done by a force in displacing a body is a basic one in the study of dynamics, and is generally defined as the product of the displacement undergone by the body, times the component of the force in the direction of the displacement. Whenever force and displacement have the same direction in common, then work equals simply force times displacement. Now it is shown in practically all texts of calculus or physics that in the case of a rigid piston and cylinder arrangement, the total work can be expressed in terms of pressure \( P \) and volume \( V \) changes by means of the formula

\[
W = \int P \frac{dV}{dt} \, dt
\]

In the cadaver experiments, the values of \( P \) and \( V \) were recorded graphically in terms of time, and were therefore available for the evaluation of the integral \( (b) \). However, it must be remembered that the formula is true strictly for a rigid tube only, and also does not take into account changes in kinetic energy. Nevertheless, the integral does represent by far the major portion of the effective cardiac work.

The problem of determining the numerical value for the integral from the graphical data was approached in several ways. The first technic involved estimating \( \frac{dV}{dt} \) from the graph of \( V \), then tabulating corresponding values of \( P \) and \( \frac{dV}{dt} \). The values of \( P \frac{dV}{dt} \) were next calculated, and a new graph prepared charting \( P \frac{dV}{dt} \) against time. The area under the curve, as measured by a planimeter, gives the desired integral. It might be remarked at this point
that the pressure here is an absolute value, and that attention must be paid to using the proper units.

A second method, depending upon the composite plotting of $P$ and $V$ on the same graph, was then tried. This graphic representation of cardiac work was described by Straub, although it does not appear to have been employed for numerical calculations. The details of our method of estimating work by this means are set forth in figure 1 and its legend. For any particular value of time $t$, the $x$- and $y$-coordinates of a point $E$ on the composite $P-V$ graph are equal to $x_E = BD = V(t)$ and $y_E = AC = P(t)$, so that $\text{Work} = \int P \, dV = \int g \, dx = \text{Area under or surrounded by the } P-V \text{ curve. Although less direct than the first method, the } P-V \text{ diagram technique proved to be considerably easier to carry through, and it was therefore used exclusively for all the final calculations.}

The integrations thus calculated by Dr. Feder compute with exactitude the work performed in raising the pressure. That performed in imparting velocity to the blood, represented by the second term of the right side of equation (a), $\frac{Mv^2}{2g}$, was calculated by Dr. Schild for each of these experiments.

Knowledge of the internal diameter of the tip of the glass aortic cannula permitted him to estimate linear velocity at the orifice. $M$, the mass moved, is usually estimated from the stroke volume and the specific gravity of blood. When the estimates were made in this way, it became obvious that the work thus represented was negligible in our experiments, being always less than 2 per cent of the total. But we believe that $M$, the mass moved at any instant, is in all probability much larger than the stroke volume, as blood is pushed on ahead of that issuing from the heart during ejection. We see no simple way of determining this quantity and so we have not attempted to correct the usual estimate of the velocity component of cardiac work, which we believe to be too small. But we see no reason to doubt that the first term of the right side of equation (a) represents the great bulk of the heart's work. Indeed, in the first part of the statistical analysis, Dr. Schild compared the results secured by both the inclusion and omission of the velocity component and found no material difference in the correlation; so we have

(4) For each time point on the $X$ axis (e.g., A on the diagram), draw a vertical line upward to the pressure curve (AC); from each of the corresponding time points on the $Y$ axis (e.g., B on the diagram) draw a horizontal line to the left to the volume curve (BD).

(5) From each point of the intersection with the pressure curve, (e.g., at C) draw a horizontal line to the left, and from the corresponding point of intersection with the volume curve, (e.g., at D) draw a vertical line upward. Extend each of these lines until they meet (e.g., CE and DE at E).

(6) Repeat this process for the entire series of time-values, and sketch a smooth curve through the points of intersection so obtained, in the upper left-hand quadrant; this derived curve is shown as the heavy line in the left upper quadrant.

(7) Estimate the magnitude of the area under this "pressure-volume" curve by any suitable method (counting squares, mechanical planimeter, linear map-measure, integration formulas, or direct graphic methods). This area represents the integral, $\int P \, dV$, and so it is the measure of work.
neglected this part of the heart's work in the results to be reported here.

Cardiac work was thus estimated by integration of the curves secured in 53 simulated systoles performed in six cadavers, in all of which blood had been used as perfusion fluid. These results are given in table 1. These data may be compared with measurements of the blood pressures and ballistocardiograms secured in the same experiments, which have been published previously.\(^6\)\(^8\) One omission deserves comment. Work was not estimated by Dr. Feder from the curves of the second systole of subject H. Z. through an oversight. The record of this "systole", mounted to provide an illustration for a previous publication, had been stored in a different place and its absence was not noticed until the statistical analyses had been largely completed. There seemed no reason to undertake the extra labor which would have been required to insert this item into the data at that time. When work is calculated approximately by formula (a), the relations found in H. Z. 2 are similar to those of the rest of the data.

Before turning the data over to Dr. Schild for statistical analysis, the question of omitting those secured in certain less perfect experiments was raised. In a previous study of methods of estimating stroke volume from blood pressure, the statistical analysis was performed twice, both with and without the inclusion of data from several less perfect experiments and the results secured by the latter method were preferred. In this analysis of data pertaining to work, we have been somewhat more rigid and we have not omitted any results except for most obvious reasons, such as the following. Of the experiments in which blood was used as perfusing fluid, we could not use three experiments, those in which curves of pulmonary artery pressures were secured, because no record of central blood pressure was taken. We also thought it wise to omit "systoles" 10 and 11 in J. W. and 5 in M. M. because the durations of "systole" so far exceeded that ever found during life, their theoretical pulse rates being 20 per minute or less. The five "systoles" secured in P. L. provided good blood pressure data, but the ballistocardiograms were imperfect—all of them lacked an I wave—so these data were used only in relating work to the blood pressure alone. After these omissions, there remained 50 "systoles" from which work could be related to blood pressure alone and 45 from which work could be related to the ballistocardiograms, all coming from experiments in which blood was used as perfusion fluid. From these data, our chief conclusions will be drawn.

---

Table 1.—"Left Ventricular" Work calculated as Pdp from Continuous Aortic Arch Blood Pressure and Cardiac Ejection Curves during the Simulation of Systole in Cadavers Perfused with Blood

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>R.R. 1</td>
<td>49.6</td>
<td>H. Z. 1</td>
<td>66.2</td>
<td>J. W. 6</td>
<td>39.9</td>
<td>M. L. 1</td>
<td>68.3</td>
</tr>
<tr>
<td>2</td>
<td>40.5</td>
<td>3</td>
<td>69.5</td>
<td>7</td>
<td>40.9</td>
<td>2</td>
<td>47.9</td>
</tr>
<tr>
<td>3</td>
<td>32.9</td>
<td>4</td>
<td>60.0</td>
<td>8</td>
<td>37.8</td>
<td>3</td>
<td>75.0</td>
</tr>
<tr>
<td>4</td>
<td>42.3</td>
<td>5</td>
<td>148.6</td>
<td>9</td>
<td>33.1</td>
<td>4</td>
<td>84.3</td>
</tr>
<tr>
<td>5</td>
<td>91.9</td>
<td>6</td>
<td>108.8</td>
<td>10</td>
<td>56.6</td>
<td>5</td>
<td>22.4</td>
</tr>
<tr>
<td>6</td>
<td>65.0</td>
<td>7</td>
<td>44.4</td>
<td>11</td>
<td>46.3</td>
<td>6</td>
<td>13.1</td>
</tr>
<tr>
<td>7</td>
<td>88.3</td>
<td>8</td>
<td>117.2</td>
<td>12</td>
<td>48.3</td>
<td>8</td>
<td>41.5</td>
</tr>
<tr>
<td>8</td>
<td>87.8</td>
<td>9</td>
<td>67.7</td>
<td>14</td>
<td>61.7</td>
<td>9</td>
<td>66.4</td>
</tr>
<tr>
<td>9</td>
<td>49.5</td>
<td>10</td>
<td>157.8</td>
<td>15</td>
<td>13.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>108.7</td>
<td>11</td>
<td>27.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>30.2</td>
<td>13</td>
<td>31.8</td>
<td></td>
<td></td>
<td>M. M. 4</td>
<td>56.3</td>
</tr>
<tr>
<td>12</td>
<td>32.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>62.3</td>
</tr>
<tr>
<td>13</td>
<td>22.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>46.3</td>
</tr>
<tr>
<td>14</td>
<td>36.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>54.9</td>
</tr>
<tr>
<td>15</td>
<td>52.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8</td>
<td>88.8</td>
</tr>
</tbody>
</table>

---

\(^6\) See STARR, ASKOVITZ, FEDER AND SCHILD, 1099.

---

STARR, ASKOVITZ, FEDER AND SCHILD

---

Table 1.—"Left Ventricular" Work calculated as Pdp from Continuous Aortic Arch Blood Pressure and Cardiac Ejection Curves during the Simulation of Systole in Cadavers Perfused with Blood

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>R.R. 1</td>
<td>49.6</td>
<td>H. Z. 1</td>
<td>66.2</td>
<td>J. W. 6</td>
<td>39.9</td>
<td>M. L. 1</td>
<td>68.3</td>
</tr>
<tr>
<td>2</td>
<td>40.5</td>
<td>3</td>
<td>69.5</td>
<td>7</td>
<td>40.9</td>
<td>2</td>
<td>47.9</td>
</tr>
<tr>
<td>3</td>
<td>32.9</td>
<td>4</td>
<td>60.0</td>
<td>8</td>
<td>37.8</td>
<td>3</td>
<td>75.0</td>
</tr>
<tr>
<td>4</td>
<td>42.3</td>
<td>5</td>
<td>148.6</td>
<td>9</td>
<td>33.1</td>
<td>4</td>
<td>84.3</td>
</tr>
<tr>
<td>5</td>
<td>91.9</td>
<td>6</td>
<td>108.8</td>
<td>10</td>
<td>56.6</td>
<td>5</td>
<td>22.4</td>
</tr>
<tr>
<td>6</td>
<td>65.0</td>
<td>7</td>
<td>44.4</td>
<td>11</td>
<td>46.3</td>
<td>6</td>
<td>13.1</td>
</tr>
<tr>
<td>7</td>
<td>88.3</td>
<td>8</td>
<td>117.2</td>
<td>12</td>
<td>48.8</td>
<td>8</td>
<td>41.5</td>
</tr>
<tr>
<td>8</td>
<td>87.8</td>
<td>9</td>
<td>67.7</td>
<td>14</td>
<td>61.7</td>
<td>9</td>
<td>66.4</td>
</tr>
<tr>
<td>9</td>
<td>49.5</td>
<td>10</td>
<td>157.8</td>
<td>15</td>
<td>13.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>108.7</td>
<td>11</td>
<td>27.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>30.2</td>
<td>13</td>
<td>31.8</td>
<td></td>
<td></td>
<td>M. M. 4</td>
<td>56.3</td>
</tr>
<tr>
<td>12</td>
<td>32.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>62.3</td>
</tr>
<tr>
<td>13</td>
<td>22.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>46.3</td>
</tr>
<tr>
<td>14</td>
<td>36.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>54.9</td>
</tr>
<tr>
<td>15</td>
<td>52.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8</td>
<td>88.8</td>
</tr>
</tbody>
</table>
In the experiments in which cadavers were perfused with water we also had a wealth of other data against which these conclusions could be tested. The technical deficiencies of these “water” experiments have been described in detail. Theoretically, differences in viscosity between water and blood would result in different pressure-flow relationships. When water was used, aortic pressure fell so rapidly after perfusion stopped that, to secure normal diastolic pressures at the onset of “systole”, we were forced to continue the femoral perfusion during systole; so the amount of fluid entering the aorta during systole exceeded that measured in the syringes. This error was certainly negligible when low aortic pressures were sought, but of larger magnitude when, to secure hypertension, we had to force water into the femoral artery under pressure. When blood was used, pressure was so much better maintained after perfusion was stopped, that we had no difficulty securing normal or hypertensive diastolic pressures at the onset of systole, although femoral inflow was always terminated just before “systole”.

Also, in these water experiments the technic of securing good records of blood pressure was mastered before that of regularly securing perfect ballistocardiograms, and these records were unsatisfactory in many of the early experiments.

For these reasons it did not seem worthwhile to undertake the labor of estimating true work by integration in these “water” experiments, but work could be readily approximated from the stroke volume measured in the syringes and the pressure in the root of the aorta by means of formula (a) without the velocity component. So, despite their technical differences it seemed well worth while to compare the data secured in the water experiments with the conclusions drawn from the blood experiments in so far as the relation of work to peripheral blood pressure was concerned.

The sample chosen for this study from the data of subjects perfused with water differed somewhat from that used in a previous study. In the present study the results secured in E. L. were omitted because, in this experiment alone, the carotid arteries were tied off, a difference of technic which might be expected to change the pressure-flow relationships, although in fact, the great majority of the values found conform with the rest of our data. In the former study, we rejected data from several “systoles” conducted in high hypertension both because of the technical difficulty mentioned above, and with the thought that the resulting pulse pressures were so large, or the blood pressure so high that such values were not to be expected during life; in the present sample no data have been rejected for such reasons. So, except for the omission of data secured in 2 systoles which could not be checked because a photograph, originally faint, faded out with the passage of time, all the 63 samples of our last series are consecutive, which is of itself ample demonstration that the technique of recording blood pressures had been mastered.

Finally, we must discuss the method of estimating the mean blood pressures used in our calculations of work made without integration. Our first inclination was to estimate mean blood pressure by the simplest possible method as follows:

\[
\text{Mean pressure} = \frac{(\text{systolic pressure} + \text{diastolic pressure})}{2}
\]

But, when we used this formula we found no improvement in the regressions which measured our ability to estimate work, so we returned to the use of formula (c) because of its slightly greater simplicity.

**Results and Discussion**

All our results deal with what has been called the external or effective work of the left ventricle, and this has been estimated from our data in many ways. For convenience of expression, we propose to designate as “true” work the values secured by integration, while the values estimated without integration, from the product of stroke volume measured in the syringes and mean central blood pressure, will be called approximate work. The results secured from estimations made from ballistocardiograms and peripheral blood pressure, or from peripheral blood pressure alone, that is, from data of a type readily available to clinicians, will be called clinical estimates of work. We shall concern ourselves solely with work per beat in this paper.
pressures were 237/119 and 233/132, the two smallest 68/31 and 90/20 mm. Hg; the two highest theoretic pulse rates were 400 and 207; the two smallest, 25 and 40 per minute; so the values covered a wide range in these experiments also.

**Tests of the approximation formula: Work = QR**

Our first step was to determine the accuracy of the approximation usually used in the estimation of the heart's work. Approximate work can be calculated both from blood pressure taken at the root of the aorta and from peripheral blood pressure. The dot diagram relating true work to the approximation calculated from stroke volume and central blood pressure is given as figure 2 and this regression equation is given as equation 76 of table 2.* From these results it is evident that work calculated from formula (a) either with or without the second term is, indeed, only an approximation of true work, but it is a good approximation. Katz,4 in experiments on isolated turtle hearts, also found the error of a similar approximation of cardiac work to be large, averaging -7 per cent and ranging from +123 per cent to -37.8 per cent. Frank,3

![Diagram](http://circ.ahajournals.org/)

Fig. 2. Tests of the simple method of estimating work most commonly used by physiologists. The estimate (vertical axis) is made from the product of stroke volume, measured in the syringes, and mean blood pressure, taken in the root of the aorta. The points shown represent data secured on 6 subjects perfused with blood. Data secured on the different subjects are represented as follows: squares, M. L.; triangles, H. Z.; circles, P. L.; dots, R. R.; crosses, J. W.; x's M. M.; The solid line is the calculated best line corresponding with regression no. 76 of table 2. The correlation coefficient between the estimate and true work is 0.95.

<table>
<thead>
<tr>
<th>Equation No.</th>
<th>Equations</th>
<th>( \sigma ) Gm.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>76</td>
<td>True Work (Gm. M.) = (-8.83 + 0.93 \text{(Stroke volume cc.) (mean aortic B. P. mm. Hg)} \times (13.6) \times (10^{-2}))</td>
<td>10.9</td>
</tr>
<tr>
<td>77</td>
<td>True Work (Gm. M.) = (-6.37 + 0.89 \text{(Stroke volume cc.) (mean femoral B. P. mm. Hg)} \times (13.6) \times (10^{-2}))</td>
<td>12.0</td>
</tr>
</tbody>
</table>

In the 50 "systoles" produced by injections of blood, the true work ranged from 13.1 to 193.9 Gm.M. which covers the range to be expected in clinical conditions and provides a diversity of values ideal for testing the accuracy of the simple methods we planned to devise. The diversity of blood pressures and theoretic pulse rates was also large in these experiments, as has been reported.5, 6 In the sample of 63 systoles produced by injections of water, the approximate work ranged from 12.6 to 150.6 Gm.M., the two largest blood

* The regression equations of this paper have been numbered serially with those of a previous communication derived from the same body of data. Other equations mentioned in this paper have been given letters. The factor concerned with the weight of mercury (13.6) and that needed to correct the decimal point to give the desired units (often \(10^{-2}\) have been left as separate items in most of the equations because we thought this would enable more readers to see how the regression lines given in the figures were related to the regression equations of the tables.
in one-third of the tests, the error exceeds 10.9 Gm.M., which is 15 per cent of the average resting healthy young adult value secured by a method to be described.

The scatter inherent in the approximation method of formula (a) is of great interest because it represents the limit of excellence possible for a really simple clinical method. It is true that catheters can be passed to the arch of the aorta in man and that the contour of the cardiac ejection curve can be estimated with reasonable accuracy by an adjusted integration of the curves of blood pressure recorded there, in the manner described in a previous communication. Therefore, means are at hand by which left ventricular work could be estimated in the clinic by integration. But the practical difficulties of such an estimation are so obvious that we were encouraged to search for methods requiring neither integration nor catheterization. In such a method, we cannot expect a standard deviation of less than 16 per cent of the mean young adult value and we can only hope to approach that value as closely as possible.

Our ability to estimate true work from stroke volume and peripheral blood pressure is given by the regression equation 77 in table 2. From the scatter about this regression, one can estimate the error entailed by computing cardiac work from estimations of stroke volume made in the clinic, and peripheral blood pressure, under the most unlikely circumstance that the cardiac output method employed had an accuracy equal to our ability to measure the output by reading a 100 cc. syringe before and after ejection. In two-thirds of the estimates, the error would be less than 18 per cent of the resting healthy young adult mean. The loss of accuracy, resulting from employing peripheral rather than central pressures, is not great and we were encouraged to seek for simple methods depending on peripheral measurements.

Estimations of Work from Ballistocardiograms and Peripheral Blood Pressure.

Since there is increasing evidence that stroke volume can be measured by ballistocardiograms of the type we employ under many conditions, though not in all, it seemed proper to discover whether true left ventricular work could be estimated from ballistocardiograms and mean blood pressure in our cadaver experiments. Accordingly, we first used the formula suggested by Tanner for estimating stroke volume from ballistocardiograms, multiplied the result by mean peripheral blood pressure and compared the resulting clinical estimate of work with true work. The correlation, r = 0.82, is good, but work is seriously overestimated, because the Tanner formula overestimates stroke volume. As it has also been found that the inclusion of a factor for body size improves the estimation of cardiac
output, the effect of using the subject’s weight and surface area in estimating work was also studied. Finally, without making an attempt to employ a stroke volume formula, we simply studied the correlation between true work and the product of mean blood pressure and the square root of the altitudes or areas of the ballistic I and J waves, with and without the inclusion of factors related to the subject’s size. One of these dot diagrams is reproduced as figure 3. The regression equations are given in table 3. In computing these equations, the ballistocardiogram measurements used have been adjusted to a calibration such that 280 Gm. displaced the light spot 1 cm. on the record.

From these results, it is evident that the correlation of such estimates and true work is extremely strong, for their correlation coefficients range from 0.82 to 0.88, values far exceeding 0.29, the level of significance for \( p = 0.05 \). The inclusion of an item related to body size gives a slightly better estimate of work. But the scatter about each of the three regressions employing Tanner’s formula with and without the size factor, equations 78, 79 and 80 in table 3, is not significantly different. Estimates made directly from measurements of the ballistocardiogram without attempting to measure stroke volume are a little better than when the stroke volume formula is employed. But once more the standard deviations about the regressions 81, 82, 83 and 84 in table 3 are not significantly different. So we have not demonstrated to our satisfaction that one of these methods is better than another.

An interesting theoretic point must be discussed here. Should one expect to measure Newtonian work by multiplying blood pressure by the amplitude of the ballistocardiogram, the latter being a force measurement? Newtonian work is related to velocity, force to acceleration. The product of ballistic amplitude and blood pressure would be more closely related to work defined as the product of mass and acceleration, integrated with respect to time. But in all probability the two kinds of work would be closely correlated under most physiologic and clinical conditions, so it should occasion no surprise that the product of ballistic amplitude and blood pressure is found strongly correlated with Newtonian work.

Certainly, left ventricular work can be roughly estimated from the ballistocardiogram and blood pressure in these experiments and one has every reason to expect that such work could be estimated with equal accuracy in the great majority of patients. But, as in most simple methods, one must envision certain limitations. In the cadaver experiments which provided the results used to make these regressions, the injections into the aorta and pulmonary artery were kept similar. But the forces producing ballistocardiograms secured during life are derived from both sides of the heart and the relation between right and left
ventricular output varies with the respiratory cycle; so an average would have to be used in conjunction with average arterial blood pressure to yield an estimate of work comparable with that of the experiments cited above. Of more moment is the fact that in certain severe clinical situations, the normal relation between the right and left ventricular forces might well be upset leading to a distorted ballistocardiogram which, when used in conjunction with arterial blood pressure, could not be expected to provide a good estimate of left ventricular work. These disadvantages would disappear in an estimate of work made from arterial blood pressure alone, so we turned our attention to the development of such a method.

*Estimations of Left Ventricular Work from Peripheral Blood Pressure Obtained by Arterial Puncture.*

In a previous communication,1 a series of formulae relating blood pressure to stroke volume were set forth. Of these, formula No. 59 relating stroke volume to peripheral pulse pressure, diastolic pressure and age seemed best adapted to our purpose. Accordingly, the stroke volume was estimated by this formula from data secured in each systole of the group perfused with blood and the result multiplied by the corresponding mean peripheral blood pressure to provide a clinical estimate of work which could be compared with true work. The dot diagram showing the relationship is reproduced as figure 4 and the regression equation is given as No. 85 in table 4. The standard deviation about the regression is 14.9 Gm.M. or 22 per cent of the mean value for left ventricular work in healthy young adults, so that in two-thirds of the estimates the error is less than this amount. Obviously, this clinical method of estimating work is a rough one. However, it must be recalled that a large part of this scatter, a standard deviation of 10.8 Gm.M., is to be attributed to the errors inherent in using any formula which does not involve integration. This method has added only 4.1 Gm.M. to the standard deviation which is the best we could hope to attain. The scatter is a little less than that of any method of estimating work based on the ballistocardiogram but the difference is too small to be significant. However, because the systemic arterial blood pressure is independent of events concerned with the right heart, one has the right to expect that methods of estimating left ventricular work from blood pressure alone would have an applicability extending over the whole clinical field.

This method of estimating left ventricular work from peripheral blood pressure alone could be further tested by making use of the results secured in the cadaver experiments in which water was employed as injection fluid, although the marked difference in viscosity of water and blood made it unlikely that the quantitative aspects of the two sets of results would be altogether similar. Therefore, we analysed the results secured in our sample of 63 consecutive systoles performed on the six cadavers perfused with water. Since true work, obtained by integration of the curves, had not
been determined in these "water" experiments, we estimated approximate work by multiplying the stroke volume measured in the syringe by mean central blood pressure, and compared it with clinical estimates of work made from the product of estimates of stroke volume from formula No. 59 and mean peripheral blood pressure. The dot diagram showing these results is given in figure 5 and the regression equation is given as No. 91 in table 6.

Our expectation of quantitative differences between results secured in cadavers perfused with blood and in those perfused with water is borne out by these results, for the slope of the regression is somewhat different from that found in the subjects perfused with blood, and the scatter is considerably greater. However, the increase of scatter may be due in large part to the necessity of using approximate work rather than true work as the target value. Despite this, the correlation is still highly significant and the general nature of the relationship developed in the subjects perfused with blood is clearly confirmed by the results secured on those perfused with water.

However, a limitation was encountered. In three systoles conducted in subject E. B., characterized by very high diastolic pressures, over 150 mm. Hg in two instances; and small pulse pressures, our stroke volume formula No. 59 estimated that the stroke volume was zero or less, although the actual stroke volumes were 13, 20 and 36 cc., differences which we hesitated to attribute to experimental error. Since it appeared that when diastolic pressure approached 150 mm. Hg, our method became less accurate, it was decided to look for other types of stroke volume formulas which might avoid the difficulty, a search in which we were encouraged by a friendly suggestion from Professor H. C. Burger of Utrecht.

Accordingly, results secured by a formula of the type originally proposed by Liljestrand

\[
\text{CLINICAL ESTIMATES OF WORK Gm.M.}
\]

\[
\text{APPROXIMATE WORK Gm.M.}
\]

**TABLE 4.—Regression Equations Relating "True" Left Ventricular Work to Clinical Estimates of Work made from Peripheral Blood Pressure Measured by Arterial Puncture in the Cadavers Perfused with Blood**

| Equation No. | Equations | \( \sigma \) Gm.M.
|--------------|-----------|--------------
| 85 | \[
\text{True work Gm.M.} = -1.67 + 0.83 [(X_4 \text{ cc.}) \text{ (mean femoral B. P. mm.Hg)}(13.6)(10^{-3})]
\] | 14.9 |
| 86 | \[
\text{True work Gm.M.} = -7.96 + 1.22 [(X_5 \text{ cc.}) \text{ (mean femoral B. P. mm.Hg)}(13.6)(10^{-3})]
\] | 16.5 |

**Fig. 5.** Tests of clinical work estimates from peripheral blood pressure. The estimates were made from femoral arterial pressure and the subjects' age, using stroke volume formula no. 59, and mean femoral blood pressure, as in the estimates in figure 4; but the data comes from six subjects perfused with water. Note that the horizontal coordinate is not true work, but approximate work, estimated as the product of stroke volume and mean aortic pressure without regard to time. Data secured from the various subjects is represented as follows: dots, A. McG.; crosses, J. I.; squares, E. S.; triangles, P. L.; circles, E. B.; and X's, E. S.; The corresponding regression equation is no. 91 of table 6. The correlation coefficient between the estimate and approximate work is 0.68.
Table 5.—New Regression Equations for Estimating Cardiac Stroke Volume from Peripheral Blood Pressure

<table>
<thead>
<tr>
<th>Equation No.</th>
<th>Equations</th>
<th>cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>87</td>
<td>Stroke volume cc. = 20 + 45 (\frac{\text{femoral pulse pressure mm.Hg}}{Z_1})</td>
<td>11.5</td>
</tr>
<tr>
<td>88</td>
<td>Stroke volume cc. = 47 + 59 (\frac{\text{femoral pulse pressure mm.Hg}}{Z_1}) - 0.58 Age years</td>
<td>9.3</td>
</tr>
<tr>
<td>89</td>
<td>Stroke volume cc. = 18 + 53 (\frac{\text{femoral pulse pressure mm.Hg}}{Z_2})</td>
<td>11.6</td>
</tr>
<tr>
<td>90</td>
<td>Stroke volume cc. = 45 + 71 (\frac{\text{femoral pulse pressure mm.Hg}}{Z_2}) - 0.59 Age years</td>
<td>9.4</td>
</tr>
</tbody>
</table>

Table 6.—Regression Equations Relating Approximate Left Ventricular Work to Clinical Estimates of Work Made from Peripheral Blood Pressure Measured by Arterial Puncture in 63 Systoles in 6 Cadavers Perfused with Water

<table>
<thead>
<tr>
<th>Equation No.</th>
<th>Equations</th>
<th>Gm.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>91</td>
<td>Approx. work (\text{Gm.M.} = 35.25 + 0.48 [(X_4)\text{ (mean femoral B. P. mm.Hg)}(13.6)(10^{-2})])</td>
<td>18.6</td>
</tr>
<tr>
<td>92</td>
<td>Approx. work (\text{Gm.M.} = 31.70 + 0.52 [(X_4)\text{ (mean femoral B. P. mm.Hg)}(13.6)(10^{-2})])</td>
<td>17.7</td>
</tr>
<tr>
<td>93</td>
<td>Approx. work (\text{Gm.M.} = 23.82 + 0.56 [(X_4)\text{ (mean femoral B. P. mm.Hg)}(13.6)(10^{-2})])</td>
<td>18.8</td>
</tr>
</tbody>
</table>

and Zander, in which pulse pressure is divided by mean pressure, were compared with the measured stroke volumes in the experiments conducted on the five cadavers perfused with blood. The simple and multiple regression equations calculated by Dr. Schild are given in Table 5.

Inspection of these results shows that the resulting stroke volume methods, though truly excellent when age is also considered, are not quite as good as the best of those published previously. That this should be true is a mathematical necessity, for regression equations in which items such as pulse pressure and diastolic pressure (or mean pressure) are treated as independent variables must have an advantage over a formulation in which the relation of pulse pressure to mean pressure is fixed. But one notes that the loss of accuracy is very small and the newer formula might have advantages when applied to other bodies of data.

Accordingly, one of the newer stroke volume formulas, No. 88 of Table 5 has been used with mean peripheral blood pressure, to provide a clinical estimate of work which could be compared with the true work. Figure 6 shows the relationship in the systoles simulated by injections of blood, the regression equation is No. 86 in Table 4. Obviously the correlation is very strong, \(r = 0.89\), while 0.27 is significant for \(p = 0.05\). The agreement between true and estimated values is excellent, but it is not quite as good as when formula 59 was employed. A similar clinical estimate of work, made by using the newer formula no. 86 to compute stroke volume, was also compared with approximate work in the 63 systoles in six cadavers in which water was used as perfusing fluid. A dot diagram of these results is given as Figure 7 and the regression equation is No. 93 in Table 6. The three systoles of subject E. B. in which the stroke volume was estimated to be zero by the older formula 59, are much better handled by the newer formula; but the correlation of the data as a whole is not im-
Fig. 6. Tests of clinical work estimates from peripheral blood pressure alone. These estimates were made from femoral arterial pressure and the subjects' age, using the ratio formula no. 88 to estimate stroke volume. Data from six subjects perfused with blood. Symbols as in figure 2. The best line corresponds with regression equation no. 86 of table 4. The correlation coefficient with true work is 0.89.

proved. By inspection of the dot diagram shown as figure 7 one sees that it is the results secured on E. S., the oldest subject studied, which disturb the correlation of the group. The values secured on E. S., although they form a beautiful regression among themselves, outlie upward and to the left of all the other data. We have no explanation for the divergence. If this subject's data are disregarded, the correlation of the rest is tremendously improved. In the data set forth in figure 5 when formula no. 59 was employed to estimate stroke volume, the results secured in E. S. do not stand as far apart from the rest, a point in favor of the formula first employed.

When inspecting figure 7, one must remember, as is the case in figure 5, that the use of approximate rather than true work as the target is certainly a considerable factor in the increase in scatter.

In short, our data do not permit us to say which of the two methods of estimating left ventricular work from peripheral blood pressure will be found superior in the clinic. Tested against data secured in cadavers perfused with blood, and in those perfused with water, in neither group are their correlation coefficients or their standard deviations about the regression significantly different. However, there is reason to suspect that the newer method may give superior results in some cases having high hypertension, and this should be kept in mind by those using these methods in the clinic.

Either of these formulas gives a test for cardiac work which, while it is a rough one, has certainly sufficient accuracy to divide human beings into three groups: those whose hearts are working normally, and those whose hearts are abnormally weak or strong. However, inspection of all the figures shows that most of the scatter is caused by differences between one subject and another, for the correlations between true work and clinical work

Fig. 7. Tests of clinical work estimates from peripheral blood pressure alone. The estimate is from femoral intra-arterial pressure and the subjects' age, using the ratio formula no. 88 to estimate stroke volume, a method similar to that used for the estimates of figure 6, but the data is from six subjects perfused with water. Note that the horizontal coordinate is approximate work. Symbols as in figure 5. The regression formula is no. 93 of table 6. The correlation coefficient between the estimates and approximate work is 0.66.
estimates in individual subjects are much stronger than those of the groups as a whole. So our ability to detect changes in the left ventricular work of any patient, due to the changing severity of disease, or to therapy, is obviously of a much higher order than is suggested by the standard deviations of the groups as a whole.

Estimations of Left Ventricular Work from Auscultatory Estimates of Blood Pressure.

The formulas discussed hitherto would serve to estimate left ventricular work from blood pressures secured from puncture of the femoral artery in any subject. Obviously, a much wider range of usefulness would be secured if these equations were adapted for use with pressures obtained by the auscultatory method as it is commonly employed. In a previous publication, regression equations relating blood pressures secured by arterial puncture with simultaneous auscultatory findings, derived from the data of Ragan and Bordley, and from those of Steele, were employed to permit estimations of stroke volume from auscultatory estimates of blood pressure. The use of these equations, No. 63 and 71 of a previous paper, together with equations permitting estimates of mean intra-arterial pressure from auscultatory measurements, will permit estimates of work from values that any doctor could secure. If the point of muffling of sounds is taken as diastolic pressure, one uses a regression from Ragan and Bordley's data, as follows:

Let \( X_s \) = an estimate of stroke volume, as follows:

\[
\text{Stroke volume (cc)} = 93 + 0.54 \text{ pulse pressure (auscultatory mm. Hg)} - 0.47 \text{ diastolic (auscultatory mm. Hg)} - 0.61 \text{ Age (years)}
\] (63)

Let \( Y_s \) = an estimate of intra-arterial mean pressure derived from equations 65* and 66, as follows:

\[
\text{Mean pressure (intra-arterial)} = -0.61 + 0.52 \text{ syst. pressure (auscultatory mm. Hg)} + 0.42 \text{ diastolic pressure (auscultatory mm. Hg)}
\] (94)

After solving these two equations one substitutes the results into equation 85 table 4

\[
\text{Work (Gm. M.)} = -1.67 + 0.83 X_s Y_s (13.6) (10^{-3})
\] (85)

\[
= -1.67 + 0.0113 X_s Y_s
\] (95)

The solution of this equation estimates the left ventricular work.

If diastolic pressure is taken as the point of disappearance of sounds, regression equations derived from Steele's data are similarly employed. That for stroke volume has already been published as equation 71. To get mean pressure, we needed a regression equation for systolic pressure so the following was estimated from Steele's data, it has not been published previously.

\[
\text{Systolic pressure (intra-arterial, mm. Hg)} = 10.62 + 1.00 \text{ systolic pressure (auscultatory, mm. Hg)}
\] (96)

and for this regression \( \sigma = 12.5 \text{ mm. Hg.} \)

The corresponding equation for diastolic pressure has already been published as equation 70.

Therefore, to estimate work from auscultatory measurements, using the disappearance of sounds as the indication of diastolic pressure, let \( X_s \) indicate the estimate of stroke volume, as follows:

\[
\text{Stroke volume (cc)} = 101 + 0.5 \text{ pulse pressure (auscultatory mm. Hg)} - 0.59 \text{ diastolic (auscultatory at disappearance of sounds, mm. Hg)} - 0.61 \text{ Age (years)}
\] (71)

Let \( Y_s \) indicate the estimate of mean pressure, as follows:

\[
\text{not been used previously, so the erroneous rendering did not effect any of our published results.}
\]

This seems a proper occasion to correct another typographical error. In table 3 of a previous publication the femoral diastolic pressure of curve No. 2, given as 85 mm. Hg, was actually 58 mm. Hg. In calculating the regression equations of that paper we used the correct value.
Mean pressure (intra-arterial mm. Hg) = \(3.21 + 0.5 \text{ systolic pressure (auscultatory mm. Hg)} + 0.52 \text{ diastolic pressure (auscultatory at disappearance of sounds, mm. Hg)}\)  \(\text{(97)}\)

After solving these equations, one substitutes the solutions \(X_4\) and \(Y_4\), for \(X_6\) and \(Y_6\) in equation 95 given above, and solves to obtain work. Jackson's nomogram \(^1\) may be used to solve equation 71.

Those choosing to use the pulse pressure to mean pressure ratio, equation 86 of table 4, as the basis for an estimate of work, could readily convert it for use with auscultatory pressures by making use of the appropriate equations given above.

Anyone accustomed to the use of a slide rule will have no difficulty with the computations needed to estimate heart work from blood pressure, although they may look complex at first glance. Our attempts to simplify the formulas have led to an interesting line of inquiry too long to be presented in this paper.

Before leaving the subject, gaps in our knowledge must be once more pointed out. In converting to permit the use of blood pressure measurements by the auscultatory method, we are assuming that intra-arterial pressures in the brachial and femoral arteries are similar. We have discussed the size of the error; \(^2\) if it exists at all it is small. But, while we do not know of data proving that these two pressures are significantly different, there is a trend in the results \(^3\) that suggests that estimates of cardiac work or stroke volume, made from our formulas, adapted for measurements of blood pressure by the auscultatory method, may eventually be found a little low.

Also, we lack data on subjects in the younger age groups. The reason for our difficulty is plain enough; young people seldom come to necropsy and when they do, because of the tragedy connected with untimely death, the case is of great interest and concern to clinician and pathologist, and is not likely to be turned over for our unorthodox investigations. Nevertheless, it is of great interest to accept the extrapolation involved and employ our formulas in the clinic on all adults until better data can be secured. The majority of people with cardiovascular disease fall into the age range covered by our data.

It also seems obvious that our formulas designed to estimate cardiac work, although successful in adults without making allowance of differences in size of the subjects, should not be used in children without further study.

**Applications of the Method.**

It seems evident that clinicians, employing the apparatus and technic they already possess, can make quantitative deductions about the work of the hearts of their patients with an accuracy far greater than we had thought likely, and certainly as good as that of many methods on which practitioners of medicine are accustomed to rely. Therefore, it seems proper to close this communication by giving an example of one way the new knowledge may be used to illuminate familiar observations. Taking the average blood pressures at each decade of life from Hunter's compilation of observations made in a quarter million healthy Americans, \(^2\) we have computed the average left ventricular work by means of formula 95 for each decade of adult life; the results are in table 7. Obviously the average heart's work declines steadily as age advances, even though health is maintained. Estimations of blood pressure such as these have been before the profession for many years, but the interpretation of these data in terms of the heart's work is new, and to us it seems most illuminating, as so many doctors have the impression that when blood pressure rises the heart's work must be increased. So it seems

<table>
<thead>
<tr>
<th>Age Decade</th>
<th>Average Blood Pressure mm. Hg</th>
<th>Left Ventricular Work Per Beat Gm.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>120/80</td>
<td>68</td>
</tr>
<tr>
<td>30</td>
<td>123/82</td>
<td>62</td>
</tr>
<tr>
<td>40</td>
<td>128/84</td>
<td>57</td>
</tr>
<tr>
<td>50</td>
<td>130/86</td>
<td>50</td>
</tr>
<tr>
<td>60</td>
<td>135/89</td>
<td>45</td>
</tr>
</tbody>
</table>
most likely that the methods described in this communication will also shed new light on the strength or weakness of the hearts of many patients coming to the clinic.

**SUMMARY**

1. Curves of cardiac ejection at each instant of systole, and curves of blood pressure at the root of the aorta, secured in experiments in which systole was simulated in cadavers, have been used as the basis of a precise estimate of "left ventricular" work by integration. The results of these precise estimates have been called true work, and it seems obvious that they far exceed in accuracy any estimates of left ventricular work that have been made in living men or mammals.

2. Results secured by the method of estimating work commonly employed by physiologists, based on the product of stroke volume and mean pressure, have been compared with true work. This method gives a good approximation of the true work. Regression equations which would improve such estimates have been derived.

3. By computing simple and multiple regression equations, we have sought means of estimating true work from measurements which could readily be made in the clinic. Such clinical estimates of work, based on the ballistocardiogram and intra-arterial measurements of peripheral blood pressure, or on peripheral blood pressure alone, have been compared with true work. In the best of these methods, in two-thirds of the estimates, the error is less than 22 per cent of the average level of cardiac work per beat of healthy young adults at rest. This accuracy seems sufficient for many clinical purposes, such as dividing the population into groups which are normal, above normal or below normal as regards left ventricular work.

4. The data clearly show that the chief cause of the scatter in such clinical methods is due to differences between individuals. The ability to detect changes in the cardiac work of most individuals greatly exceeds that indicated by the figures given above.

5. Formulas have been derived which permit estimates of left ventricular work from auscultatory measurements of blood pressure, so that rough estimates could be made by anyone practicing medicine.

6. By means of the average values for blood pressure of healthy Americans at rest, and the formula mentioned above, average left ventricular work has been estimated for each decade of life from 20 to 60 years. Despite the well-known rise in blood pressure, the average heart work declines steadily as life advances. At 60 years of age the average work per beat is about two-thirds of the average found at 20 years of age.

**SUMMAARIO IN INTERLINGUA**

Le labor "sinistro-ventricular" pote esser estimate con un alte grado de exactitude in experimentos con cadaveres in quse curvas de pression e curvas del ejection cardiae es registrare pro omne punctos del systole. Considere tal exacte estimationes como criterio in le evaluatio del resultatos, nos ha interpretate le cerca de methodos que permiterea le estimation del labor cardiae super le base de measuraciones de un genere executabile in le clinic.

Nos ha succeede a derivare formulas quse permitte le estimation del labor sinistro-ventricular super le base de measuraciones auscultatorii del pression sanguine. Assi iste metodo pote esser usate per omne practico medical.

**REFERENCES**


8 —: Units for the expression of both static and dynamic work in similar terms and their application to weight-lifting experiments. J. Appl. Physiol. 4: 21, 1951.


11 Starr, I. and Schnabel, T. G., Jr.: Studies made by simulating systole at necropsy. V. Estimation of the contour of the left ventricular ejection curve by an adjusted integration of the aortic blood pressure curve. J. Appl. Physiol. 7: 273, 1954.


ISAAC STARR, S. I. ASKOVITZ, W. FEDER and A. SCHILD

Circulation. 1955;12:1005-1021
doi: 10.1161/01.CIR.12.6.1005

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1955 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/12/6/1005

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org//subscriptions/