The Journal of Clinical Investigation

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J Clin Invest. 1952;31(2):209-216. https://doi.org/10.1172/JCI102594.

Research Article

A COMPARISON OF THE ESTIMATION OF THE BASAL CARDIAC OUTPUT FROM A LINEAR FORMULA AND THE "CARDIAC INDEX"[1]

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(Submitted for publication July 27, 1951; accepted November 23, 1951)

It is customary to express the cardiac output of man in units of body size, usually in the form of the cardiac index which is simply the gross cardiac output in liters of blood per minute divided by the surface area of the body. The use of the cardiac index implicitly assumes that the cardiac output normally is directly proportional to the surface area of the body with the prediction line going through the origin of the X and Y axes. Tanner (1, 2) has recently pointed out that errors arise in using cardiac index as a criterion for prediction of cardiac output when strict proportionality is not present. In this situation, the regression line which describes the best linear fit for any group of data differs from the line defined by the cardiac index. Under these conditions the cardiac index will overestimate or underestimate the expected value for an individual in the extreme range of the body size and comparisons of population groups with reference to the cardiac index will be inexact unless the surface areas of the two population groups are identical. Tanner (1) used the relationship of stroke volume to body weight as an example of such errors but did not provide an analysis of the errors involved in the cardiac index.

A large percentage of the cardiac output data in the literature is expressed in terms of the cardiac index. Recently standards for the low-frequency, critically damped ballistocardiograph have been published exclusively in terms of this ratio by Gregersen and Nickerson (3). It is the purpose of this paper to examine the validity of the cardiac index as a standard with special reference to its usefulness in predicting the cardiac output of individuals.

SUBJECTS AND CONDITIONS

Cardiac output and surface area data were obtained on 48 healthy, male, university students who were between the ages of 18 to 30. All of these men were studied with the low-frequency, critically damped ballistocardiograph. Duplicate records were made in each case. Ten cardiac complexes were analyzed in each record. The cardiac output of 34 of these men was determined with the acetylene method. Quadruplicate determinations by this method were made in 22 men, duplicates in 12. All men reported to the Laboratory without breakfast and lay on a bed for 20 minutes before observations were begun. All observations were carried out in an air conditioned room which was maintained at a temperature of 78 ± 2° F. The subjects were studied during the months of October, November, December, March and April.

METHODS

Cardiac output estimations by the acetylene method were made following the Grollman procedure. The final computation applied the correction given by Chapman and associates (4) so that the absolute values are in harmony with those obtained from the direct Fick (catheter) method.

Cardiac output estimations by the ballistocardiographic method employed the low-frequency, critically damped apparatus described by Nickerson and Curtis (5). The computational method was that of Nickerson, Warren and Brannon (6); this has also been calibrated against the catheter method. The surface area of all subjects was determined by the formula of Dubois.

SELECTION OF DATA FROM THE LITERATURE

Data in the literature which may be used for the purpose of this discussion have been reviewed by Tanner (1). In the present analysis we have included the two series presented by Tanner in which the cardiac output was determined by the high-frequency ballistocardiograph on males, the acetylene method and the ethyl iodide method. Tanner pointed out, from statistical considerations, that the two series of measurements on normal individuals which were carried out by the direct Fick method appear to have been drawn from different populations. One of these series of measurements, which was collected by Cournand's group (7), was carried out in New York and the other by Stead, Warren, Merrill, and Brannon (8) was done in Atlanta, Georgia. Since the publication of Tanner's work, data on 19 normal males age 20 to 40 have been gathered in the same laboratory in Minneapolis by Chapman and associates (4) and Ebert, Borden, Wells, and Wilson (9). It seems reason-

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[1] This work was supported in part by the Research Grants Division of the U. S. Public Health Service.

able to assume that at least part of the difference between the data obtained in Atlanta and New York was due to climate. We have, therefore, excluded the Atlanta data and pooled the Minneapolis data and that part of the New York data obtained on young men between the ages of 20 to 40.

STATISTICAL METHODS

Methods for calculating standard deviations, correlation coefficients, and constants for regression functions can be found in any elementary textbook of statistics. A few methods have been employed which should be stated in some detail to avoid confusion.

The first of these has to do with testing the significance of correlation coefficients. For this purpose we have used Fisher's z transformation (10). This was done with the following equation:

$$z = \ln_e \left\{ \frac{1 + r}{1 - r} \right\}^{\frac{1}{2}}, \qquad (1)$$

where r is the correlation coefficient. When this is done, z is normally distributed with variance equal to 1/(n − 3).

TABLE I

Basal cardiac output data obtained with the low-frequency, critically damped ballistocardiograph along with some of the characteristics of the subjects

Subject	Age	Height	Weight	Blood pressure	Heart rate	Stroke volume	Cardiac output
	(years)	*(cms.)*	*(kgs.)*				
CVD 104	23	163	53.0	115/82	68	82.5	5.61
CVD 3	25	178	58.5	110/80	69	76.2	5.26
Scan.	19	181.6	54.9	104/60	70	87.7	6.14
Forth.	29	175.9	65.5	118/70	60	109.3	6.56
CVD 13	22	176	70.1	115/72	54	114.4	6.18
CVD 56	24	168	51.7	110/66	65	78.9	5.13
Willem.	20	175.9	60.5	114/78	65	103.5	6.73
Erick.	20	178.1	55.5	110/66	58	97.5	5.66
Traut.	22	179.1	69.5	120/73	67	97.5	6.53
CVD 119	20	178	71.5	172/66	70	110.5	7.74
CVD 17	22	178	69.2	103/75	54	90.7	4.90
Strau.	21	170.8	71.8	125/85	64	129.2	8.27
CVD 162	24	181	73.5	126/82	64	116.9	7.48
CVD 7	25	166	67.0	122/75	54	92.0	4.97
CVD 41	25	168	76.5	111/70	55	92.7	5.10
Svig.	25	178.4	77.2	145/85	70	130.0	9.10
Torger.	24	178.4	76.1	124/76	62	122.9	7.62
Nayya	28	165.1	54.1	110/76	76	86.3	6.56
CVD 120	24	175	79	139/84	73	121.6	8.88
Alterm.	20	168.3	73.4	114/73	64	112.0	7.17
CVD 110	20	174	85	118/83	60	102.8	6.17
Ortlip.	20	167	80.7	109/72	50	121.2	6.06
CVD 31	26	174	95.5	119/89	69	92.2	6.36
Erwi.	27	183.5	102.0	120/80	71	154.5	10.97
Podem.	23	173.7	89.5	104/67	59	115.2	6.80
Duckw.	24	183.5	135.2	126/83	74	144.2	10.67
Teitenb.	19	189.2	83.7	106/73	66	125.2	8.26
Boss.	25	182.9	95.9	122/78	66	100.5	6.63
Dav.	25	173	73.0	121/78	62	112.3	6.96
Wies	20	181.6	84.9	144/87	56	139.2	7.80
Christen.	21	179.1	84.0	126/80	56	106.8	5.98
Evang.	17	177.8	66.8	118/72	59	101.5	5.99
Lindl.	21	174.6	62.2	120/77	59	88.1	5.20
Hof.	24	172.1	70.1	125/82	61	121.6	7.42
Carls.	24	178.4	62.3	122/66	72	92.7	6.68
Donald.	20	184.2	71.1	119/70	57	95.8	5.46
Koch.	24	174.6	76.6	120/82	77	86.3	6.64
Adam.	23	171.5	75.5	130/84	65	119.1	7.74
CVD 21	24	176	78.3	126/82	63	82.2	5.18
CVD 23	26	174	77.2	121/83	51	100.4	5.13
CVD 30	22	185	74.5	120/71	61	112.0	6.85
CVD 31	26	174	95.5	119/79	69	92.1	6.36
CVD 45	24	188	85.2	112/75	79	87.2	6.89
CVD 50	22	183.0	79.0	134/91	64	133.2	8.53
CVD 59	22	183.0	71.5	140/88	63	94.7	5.97
CVD 109	24	182.0	93.3	155/88	63	154.1	9.71
CVD 144	21	170	63.5	119/80	65	81.0	5.27
CVD 145	19	176	96	132/86	76	87.0	6.61
Mean	22.8	176.4	75.7	122.0/77.5	64.1	106.2	6.79
S. D.	2.59	5.99	15.1	13.9/ 7.2	6.98	19.7	1.43

The root mean square of sums of deviations of observations from corresponding hypothetical values is given by

$$(2)\qquad \left\{\frac{\Sigma(Y-\tilde{Y})^2}{n}\right\}^{\frac{1}{2}},$$

where Y is the observed value and $\tilde{Y}$ is the corresponding hypothetical value.

When Y equals the mean of the observed values ($\overline{Y}$) expression (2) reduces to the sample estimate of the standard deviation, s_Y.

The cardiac index line is defined by the equation

$$(3)\qquad \hat{Y} = kX,$$

where $k=\overline{Y}/\overline{X}$. Then the root mean square of deviations from this line is given by the special case of expression (2), where $\tilde{Y} = \hat{Y}$. After some manipulation this expression reduces to

$$(4)\qquad \{s_Y^2 - 2\cdot r\cdot \overline{Y}/\overline{X}\cdot s_X\cdot s_Y + (\overline{Y}/\overline{X})^2 s_X^2\}^{\frac{1}{2}},$$

where s_Y and s_X are defined above. Finally the root mean square of deviations of observations from the regression line was calculated by the expression

$$(5)\qquad \left\{\frac{\Sigma(Y-Y')^2}{n}\right\}^{\frac{1}{2}} = s_Y\{1-r^2\}^{\frac{1}{2}},$$

where $Y' = a + bX$.

The limits of confidence of the regression line are given by the expression (11)

$$(6)\qquad Y' \pm 2\sigma_{Y'},$$

where

$$(7)\qquad \sigma^2_{Y'} = \sigma^2_{Y-Y'}\left\{\frac{1}{n} + \frac{(X-\overline{X})^2}{ns_X^2}\right\}.$$

The sample estimate of $\sigma^2_{Y-Y'}$ is given by

$$(8)\qquad \frac{\Sigma(Y-Y')^2}{n-2} = \frac{ns_Y^2}{n-2}\{1-r^2\}.$$

The sample estimate of σ_Y is therefore given by

$$(9)\qquad \left\{\frac{ns_Y^2}{n-2}\cdot[1-r^2]\cdot\left[\frac{1}{n} + \frac{(X-\overline{X})^2}{ns_X^2}\right]\right\}^{\frac{1}{2}}.$$

RESULTS AND ANALYSIS

The individual cardiac outputs obtained with the low-frequency, critically damped ballistocardiograph and certain characteristics of the individuals are presented in Table I. The cardiac outputs determined by the corrected acetylene method will be presented in detail elsewhere (12).

The means and standard deviations of the cardiac outputs and surface areas in the several series of measurements, together with the references, are presented in Table II. Table III presents the correlation coefficients (r) between cardiac output and surface area in the different groups. It will be noted that in the two series of measurements carried out with the high-frequency ballistocardiograph, the value of r is small compared to that obtained when other methods are employed to measure cardiac output.

TABLE II

Cardiac output and surface area data on healthy men

N = number, S.D. = standard deviation

Author	Method	N	Cardiac output, *l/min.*		Surface area, *m²*	
			Mean	S.D.	Mean	S.D.
Starr (13)	B. C. G.*	108	5.73	1.10	1.89	0.13
Tanner (1)	B. C. G.*	50	6.21	0.79	1.85	0.12
Lewis (14)	Acetylene	80	4.07	0.51	1.79	0.14
Grollman (15)	Acetylene	37	4.01	0.35	1.81	0.13
Starr (16)	Ethyl iodide	22	4.47	1.05	1.83	0.13
Selected†	Direct Fick	26	6.39	1.37	1.89	0.16
L. P. H. (12)	Corrected acetylene	34	5.54	0.87	1.89	0.19
L. P. H. (17)	B. C. G.‡	48	6.79	1.43	1.92	0.18

* High-frequency ballistocardiograph.

† Cournand and associates (7), Chapman and associates (4), and Ebert and associates (9).

‡ Low-frequency, critically damped ballistocardiograph.

Neither of the values of r for the high-frequency ballistocardiograph is significantly different from zero and we may conclude that this instrument gives cardiac outputs which do not distinguish between large and small individuals. This is also true of the ethyl iodide method. On the other hand, the direct Fick (catheter), corrected acetylene, low-frequency, critically damped ballistocardiograph and acetylene methods, all yielded values for r which are significantly different from zero. Thus these methods definitely distinguish

TABLE III

Coefficients of correlation between the cardiac output, in liters per minute, and the surface area obtained in the several series presented in Table I, along with the 5 per cent confidence intervals for each value of r

The last column gives the value of r which must be reached if the calculated value of r is considered to be different from zero.

Author	Method	5% confidence values			
		r	Lower	Upper	r at 5% level sig.
Starr	B. C. G. high frequency	0.14	−0.05	0.32	0.20
Tanner	B. C. G. high frequency	0.17	−0.11	0.43	0.28
Lewis	Acetylene	0.50	0.32	0.65	0.22
Grollman	Acetylene	0.53	0.25	0.73	0.33
Starr	Ethyl iodide	0.34	−0.10	0.66	0.42
Selected	Direct Fick, catheter	0.54	0.19	0.77	0.39
L. P. H.	Corrected acetylene	0.60	0.33	0.78	0.34
L. P. H.	B. C. G. low frequency	0.60	0.38	0.76	0.28

TABLE IV

The regression constants relating cardiac output to surface area

The constant b is the slope of the regression line and a is the intercept on the cardiac output (Y) axis.

Method	Regression constants	
	b.	a.
High-frequency ballistocardiograph*	1.12	4.14
Low-frequency ballistocardiograph	4.74	−2.29
Corrected acetylene	2.75	0.34
Direct Fick (catheter)	4.48	−2.11

* Data of Tanner (1)

between large and small individuals. It should be noted that the range of body sizes included in the various samples is roughly the same. The standard deviation of the surface area of Starr's subjects was 0.13. Grollman's subjects had an identical standard deviation for surface area yet in the first case the r relating cardiac output and surface area was 0.14 and in the second 0.53.

On testing the significance of the differences between the several r's presented in Table III, transformed into the z values (10), "student's" t test was used to test the null hypothesis that $z_1 = z_2$ where z_1 and z_2 are the values of the transformed r's under consideration. It was found that the values of the r's obtained with the high-frequency ballistocardiograph differed significantly from those obtained by any of the other methods except that of the ethyl iodide. Tanner (1) has pointed out that the repeatability of the high-frequency ballistocardiograph is high. The test retest correlation coefficient in his series was 0.91. This means that the failure of the high-frequency ballistocardiograph to correlate well with surface area is not due to a large random error in the method. It follows by inference from this that the high-frequency ballistocardiograph is measuring something quite different from that measured by the other methods of determining cardiac output.

Four of the series of cardiac output measurements presented in Tables II and III have been selected for a detailed analysis. The age range of the subjects varied between 18 and 40. The methods and regression constants are presented in Table IV.

The raw data obtained with the low-frequency, critically damped ballistocardiograph are plotted in Figure 1. Both the regression line and the cardiac index line are included in the figure. The cardiac index line was constructed in the usual manner, *i.e.*, the point on the graph given by the mean of the surface area of the group and the

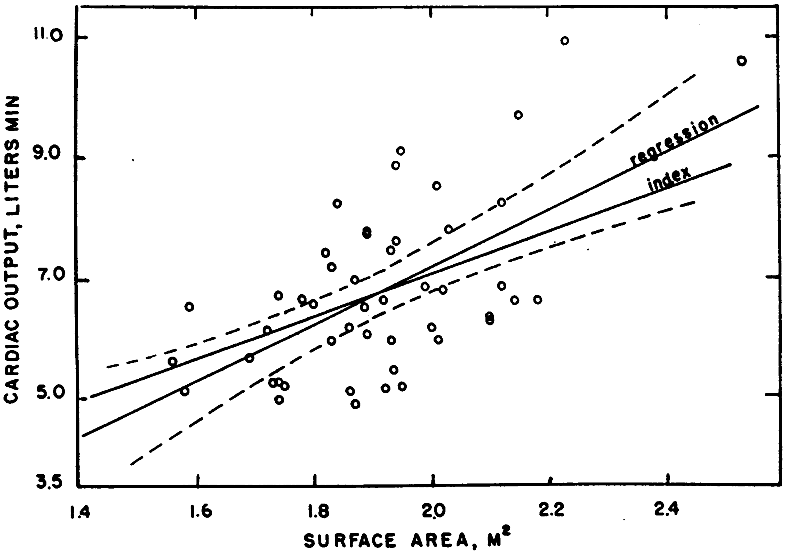

FIG. 1. THE RELATIONSHIP BETWEEN SURFACE AREA OF THE BODY IN SQUARE METERS AND THE BASAL CARDIAC OUTPUT IN LITERS PER MINUTE

The regression line and the cardiac index line are indicated in the figure. The dotted lines are the limits of confidence of the regression line and enclose the range in which will be found the regression lines derived from 95 out of 100 repetitions of this experiment on random samples of this size.

mean of the cardiac output was found and a line was drawn through this point and the zero point. The slope of the regression line and the means of the surface area and cardiac output are subject to sampling error. The possible extent of these errors is indicated by the dotted lines on Figure 1 (11). The range included between these lines includes the regression lines which will be found 95 times in 100 repetitions of this experiment on random samples of this size.

It is apparent that while the regression line is the best possible description of the data at hand, there is a great deal of uncertainty as to the slope of a regression line describing the relationship of surface area and cardiac output of the general population. It is interesting to note that with the exception of the high-frequency ballistocardiograph, the four methods considered in Table IV give regression lines whose limits of confidence enclose the cardiac index line. It is possible, then, that errors in sampling could account for the differences between the cardiac index line and the regression lines of the various samples studied.

To test the relative validity of the linear and the cardiac index methods of prediction, we have elected to use the criteria of accuracy of prediction. This method has been used in the past by Berkson and Boothby (18) to examine the validity of predicting basal metabolism from surface area ratios. Table V gives the root mean square deviations of the observed cardiac outputs minus those calculated by the regression line and the cardiac indices for the four series of measurements. It will be noted that the high-frequency ballistocardiograph gives the largest difference between the root mean squares of the regression line and the cardiac index while the other methods show only small or no difference between the two standards. Comparisons between the absolute magnitudes of the root mean squares of the four methods should be made with caution since multiple determinations for each individual were used to gather data for two of the methods and were not used for the others.

TABLE V

The comparison of the root mean square deviations of observed minus calculated cardiac outputs in liters per minute

	High-frequency B. C. G.*	Low-frequency B. C. G.	Corrected acetylene	Direct Fick
Regression line	0.80	1.14	0.70	1.15
Cardiac index	0.85	1.16	0.70	1.17
Per cent increase	6.3	1.8	0	1.7

* Data of Tanner (1)

TABLE VI

The difference between the cardiac output as predicted by the regression line and that predicted by the index line for different values of surface area

The data for this example are drawn from the series of measurements obtained with the low-frequency ballistocardiograph.

C.O. predicted by \ Surface area, m^2	1.60	1.70	1.80	1.90	2.00	2.10	2.20
Regression	5.29	5.77	6.24	6.72	7.19	7.66	8.14
Cardiac index	5.65	6.00	6.35	6.71	7.06	7.41	7.77
Difference	−0.36	−0.23	−0.11	0.01	0.13	0.25	0.43
Percent of value predicted by reg.	6.8	4.0	1.8	0.2	1.8	3.3	5.3

It is advantageous to compare the variability around the cardiac index line with that around the regression line in terms of the variance (mean sum of squares of deviations) which in this case is simply the square of the figures presented in the body of Table V. This allows us to make proper comparisons of the percentage of excess variability exhibited by the cardiac index over that of the regression standard. Since it can be shown that the variance of the cardiac output from the regression and cardiac index lines are additive, we may write the following expression:

1) $$V_{CI} = V_R + V_{ex},$$

where V is the variance and the subscripts stand for cardiac index, regression and excess, respectively. The percentage of excess variance then becomes

2) $$P_{ex} = \frac{V_R + V_{ex}}{V_R}.$$

Applying equation 2, we find that the excess variance of the index line as per cent of the total variance of the regression line is 13.0 per cent in the case of the high-frequency ballistocardiograph, 3.6 per cent for the low-frequency ballistocardiograph, 2.6 per cent for the direct Fick and a negligible amount for the corrected acetylene procedure. Again the high-frequency ballistocardiograph appears to be quite different from the other methods examined here since the use of the cardiac index

TABLE VII

Errors arising from the use of the cardiac index in comparing groups whose mean surface areas are different

The case considered here is that of two groups, both with normal cardiac outputs, drawn from the population described in Figure 1.

Surface area		Cardiac index		Error	Error % of ref. group
Ref. group	Exp. group	Ref. group	Exp. group		
1.90	1.80	3.54	3.46	0.08	2.2
1.90	1.70	3.54	3.39	0.15	4.2
2.00	1.70	3.59	3.39	0.20	5.6
2.10	1.70	3.65	3.39	0.26	7.1
2.20	1.60	3.70	3.30	0.40	10.8

line increases the excess variance by 3.5 times or more than that found with other methods.

To complete the picture, a more detailed description of the errors resulting from the use of the cardiac index in the extremes of body size is useful. An analysis of these errors in the case of the low-frequency ballistocardiograph is presented in Table VI. The errors are a little larger in the case of the small individual as compared to the large and they will not be over 7 per cent in the range of size usually encountered in the northern part of the United States.

Comparisons between the four methods under consideration have been made by examining the figures at one extreme of surface area. For this purpose, the standard deviations of the four series of surface area measurements were averaged and multiplied by 2. This figure was 0.321 square meters of surface area. It was found that in per cent of the value predicted by the regression line at 0.321 square meter above the mean for each group, the error of the cardiac index line was 11.6 per cent for the high-frequency ballistocardiograph, 4.7 per cent for the low-frequency ballistocardiograph, 4.7 per cent for the direct Fick and 0.9 per cent for the corrected acetylene method.

While the error involved in predicting the cardiac output of an individual is small compared to the total variability observed in the cardiac output, the problem of comparing groups is quite different since small differences can be shown to be significant when large groups are involved. Examples of the error arising when two groups whose cardiac output is normal but whose surface area is different are compared and presented in Table VII. It is apparent that if one were interested in comparing a group of very large men with a group of very small men by means of the cardiac index, it would be possible to reach entirely unjustified conclusions.

DISCUSSION

The inference that the high-frequency ballistocardiograph is measuring something only indirectly related to the cardiac output, from the fact that it gives estimates of cardiac output which for all practical purposes are unrelated to body size, has support from other evidence. It has been known for some time that this method gives inaccurate estimates of the cardiac output in the presence of surgical shock (19). Unexplained discrepancies related to the pulse rate in alternative methods of calculating the cardiac output from records of the high-frequency ballistocardiograph have been noted (20). Finally Starr, Horwitz, Maycock and Krumbhaar (21) have recently proposed that the high-frequency ballistocardiograph be used to obtain a measure of cardiac strength, a function which is indirectly related to cardiac output.

Kleiber (22) has pointed out that equations describing physiological data which convey physiological meaning may have value even though in a given sample of the population a more complicated but less meaningful equation would give a better fit to the available data. The cardiac index appears to be a case in point. We have shown that three closely related methods in current use give cardiac outputs which are related to surface area in such a way that the use of the cardiac index adds only a small (less than 3.6 per cent) additional variance over that found by the more efficient least squares method. It should be remembered that even in the best situation the variability attributable to differences in surface area account for only 20 per cent of the total variability observed. The cardiac index is a physiologically meaningful standard which, although somewhat less efficient than the regression line, does not impose an unacceptable penalty when used as a standard to predict the cardiac output of individuals. It is understood that when the cardiac index is used as a standard for individual predictions, it should always be accompanied by precise age specifications since the cardiac index varies with age.

However, when large groups of individuals are to be compared, the data should be examined carefully for a possible statistical artifact whose magnitude will depend on the size of the difference in surface area between groups. The solution to this problem is considered to be beyond the scope of this paper and will be considered in detail elsewhere.

It may also be noted that with the available statistical tools, it is not possible to make probability statements as to whether the cardiac index line is actually different from the regression line. The difficulty lies in the fact that we have no knowledge of the sampling differences between slopes of the two equations. If this distribution was available, one could test the hypothesis that the difference between the slopes of the two equations was equal to zero. Then the decision as to whether the cardiac index line is, in fact, a practical method of predicting the cardiac output could be made with confidence corresponding to the probability found.

Many physiologists would insist that the cardiac index line must go through zero. If this is the case and the regression line and cardiac index line are not identical then the cardiac output surface area relationship is not linear but curvilinear. This is an important point since the validity of the above analysis is dependent on the assumption of a linear relationship between the two variables. Unfortunately this question cannot be completely resolved. One can only test for the presence of a curvilinear relationship. On applying the proper statistical test (23), it was found that a definite curvilinear relationship between surface area and cardiac output could not be demonstrated.

SUMMARY AND CONCLUSIONS

1. The relationship between surface area and cardiac output has been examined in a series of observations carried out with the high-frequency ballistocardiograph, the low-frequency, critically damped ballistocardiograph, the ethyl iodide method, the acetylene method, the corrected acetylene method and the direct Fick (catheter) procedure of estimating cardiac output.

2. The high-frequency ballistocardiograph gives estimates of cardiac outputs which are not related to body size (surface area) and is an unsatisfactory method from this point of view. The same is true of the ethyl iodide procedure. The low-frequency, critically damped ballistocardiograph, the acetylene method, the direct Fick (catheter) procedure and the corrected acetylene all distinguish between large and small individuals in a satisfactory manner.

3. The relative efficiencies of the cardiac index and the regression lines as methods for the prediction of the cardiac output from body size (surface area) have been examined in data obtained with four methods for the determination of cardiac output which are in current use.

4. When the cardiac index was used as a standard for data obtained with the low-frequency, critically damped ballistocardiograph, the corrected acetylene and the direct Fick (catheter) procedure, it was found that the variance of the standard increased by only 3.6 per cent or less (less than 2 per cent in terms of the root mean square) over that found when the regression line was used.

5. The limitations of the use of the cardiac index have been discussed.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the cooperation of Dr. Fredrick de la Vega and Dr. Paul Winchell and the assistance of Mr. Walter Carlson and Miss Laura Werner in the collection of the cardiac output measurements.

REFERENCES

1. Tanner, J. M., The construction of normal standards for cardiac output in man. J. Clin. Invest., 1949, **28**, 567.
2. Tanner, J. M., Fallacy of per weight and per surface area standards and their relation to spurious correlation. J. Appl. Physiol., 1949, **2**, 1.
3. Gregersen, M. I., and Nickerson, J. L., Relation of blood volume and cardiac output to body type. J. Appl. Physiol., 1950, **3**, 329.
4. Chapman, C. B., Taylor, H. L., Borden, C., Ebert, R. V., and Keys, A., Simultaneous determinations of the resting arteriovenous oxygen difference by the acetylene and direct Fick methods. J. Clin. Invest., 1950, **29**, 651.
5. Nickerson, J. L., and Curtis, H. J., The design of the ballistocardiograph. Am. J. Physiol., 1944, **142**, 1.
6. Nickerson, J. L., Warren, J. V., and Brannon, E. S., The cardiac output in man: studies with the low frequency, critically-damped ballistocardiograph and the method of right atrial catheterization. J. Clin. Invest., 1947, **26**, 1.
7. Cournand, A., Riley, R. L., Breed, E. S., Baldwin, E. deF., and Richards, D. W., Jr., Measurement of cardiac output in man using the technique of catheterization of the right auricle or ventricle. J. Clin. Invest., 1945, **24**, 106.

8. Stead, E. A., Jr., Warren, J. V., Merrill, A. J., and Brannon, E. S., The cardiac output in male subjects as measured by the technique of right atrial catheterization. Normal values with observations on the effects of anxiety and tilting. J. Clin. Invest., 1945, **24**, 326.
9. Ebert, R. V., Borden, C. W., Wells, H. S., and Wilson, R. H., Studies of the pulmonary circulation. I. The circulation time from the pulmonary artery to the femoral artery and the quantity of blood in the lungs in normal individuals. J. Clin. Invest., 1949, **28**, 1134.
10. Fisher, R. A., Statistical Methods for Research Workers. Hafner Publishing Co., New York, 1950, pp. 197–201.
11. *Ibid.*, pp. 131–136.
12. Taylor, H. L., Brozek, J., and Keys, A., Relationship between basal cardiac output and body composition with special reference to obesity. Federation Proc., 1951, **10**, 135.
13. Starr, I., and Schroeder, H. A., Ballistocardiogram. II. Normal standards, abnormalities commonly found in diseases of the heart and circulation, and their significance. J. Clin. Invest., 1940, **19**, 437.
14. Lewis, W. H., Jr., Changes with age in the cardiac output in adult man. Am. J. Physiol., 1938, **121**, 517.
15. Grollman, A., Physiological variations in the cardiac output of man. VI. The value of the cardiac output of the normal individual in the basal, resting condition. Am. J. Physiol., 1929, **90**, 210.
16. Starr, I., Donal, J. S., Margolies, A., Shaw, R., Collins, L. H., and Gamble, C. J., Studies of the heart and circulation in disease; estimations of basal cardiac output metabolism, heart size, and blood pressure in 235 subjects. J. Clin. Invest., 1934, **13**, 561.
17. Taylor, H. L., Winchell, P., and de la Vega, F., Observations on the low frequency critically damped ballistocardiograph. To be published.
18. Berkson, J., and Boothby, W. M., Studies of the energy of metabolism of normal individuals. A comparison of the estimation of basal metabolism from (1) a linear formula and (2) "surface area." Am. J. Physiol., 1936, **116**, 485.
19. Cournand, A., Riley, R. L., Bradley, S. E., Breed, E. S., Noble, R. P., Lauson, H. D., Gregersen, M. I., and Richards, D. W., Studies on the circulation in clinical shock. Surgery, 1943, **13**, 964.
20. Galdston, M., and Steele, J. M., Critique of area and height formulae for estimating cardiac output from the ballistocardiogram. J. Appl. Physiol., 1950, **3**, 229.
21. Starr, I., Horwitz, O., Maycock, R. L., and Krumbhaar, E. B., Standardization of the ballistocardiogram by simulation of the heart's function at necropsy; with a clinical method for the estimation of cardiac strength and normal standards for it. Circulation, 1950, **1**, 1073.
22. Kleiber, M., Physiological meaning of regression equations. J. Appl. Physiol., 1949–50, **2**, 417.
23. Fisher, R. A., *op. cit.*, pp. 255–258.