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Direct Fick cardiac output: Are assumed values of oxygen consumption acceptable?

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The use of assumed values of oxygen consumption has become an accepted practice in the calculation of direct Fick cardiac output. A survey showed that the assumed values in common use were derived from basal metabolic rate studies on normal subjects, a use which may not be valid. We have compared previous assumed values based on basal metabolic rate or cardiac catheterization studies with those obtained by direct measurement in 80 patients (age range 38–78 years) with various cardiac disorders. Comparison of the assumed and directly measured values of indexed oxygen consumption and the cardiac index showed large discrepancies, with over half the values differing by more than ±10% and many by more than ±25% from the measured value. Assumed values of oxygen consumption should be used with caution when calculating cardiac output during cardiac catheterization procedures, because large errors can result. The equations of LaFarge and Miettinen gave the closest approximation to the measured data and their use is recommended in preference to values predicted from basal metabolic rate studies.

Introduction

The measurement of oxygen consumption ($\dot{V}O_2$) is an essential component for the determination of cardiac output according to the Fick principle[1]. However, the direct measurement of $\dot{V}O_2$ can be an uncomfortable procedure for the patient. It requires breathing via a mouthpiece for a reasonable period of time to allow the patient to become accustomed to this form of breathing and to obtain $\dot{V}O_2$ under 'basal conditions'.

As an alternative, it has become the accepted practice of cardiac catheterization laboratories to use assumed values of $\dot{V}O_2$ either as a routine or when the measurement of $\dot{V}O_2$ is unobtainable due to poor patient co-operation or technical failures.

A questionnaire sent to 35 cardiac catheterization laboratories in the U.K. asking for details of the methods used to estimate cardiac output revealed that 12 of the 26 centres who replied used the direct Fick method to estimate cardiac output, either as a routine or as a research procedure. The remaining centres used thermodilution or dye dilution. Nine of the 12 centres using the direct Fick method employed assumed values for $\dot{V}O_2$ either as a routine or when $\dot{V}O_2$ could not be estimated directly. Four different sets of data were employed to estimate $\dot{V}O_2$[2–5]. Four centres used the data of Boothby *et al.*[2], two the data of Robertson and Reid[3], two the data of Fleisch[4], and one that of Aub and Dubois[5]. Six of the centres were not aware of the source of the assumed values they used. As these studies were originally produced as normal standards for the measurement of basal metabolic rate, their application in calculating direct Fick cardiac output may be inappropriate.

The purpose of this study was to compare assumed values of $\dot{V}O_2$ with those measured directly in order to determine (1) which, if any, gave comparable estimates of measured $\dot{V}O_2$, and (2) the disparity in results when using these estimates in the cardiac index (CI) calculation.

Subjects and methods

SUBJECTS

Studies were performed on patients with various cardiac disorders undergoing routine left and right heart cardiac catheterization as part of their assessment. Patients were not sedated prior to the catheter procedure. Height and body mass were measured the following day, with the patient in stockinged

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feet, and wearing light clothing. Body surface area (BSA) was calculated according to Dubois and Dubois[6].

DIRECT FICK CARDIAC OUTPUT

The direct Fick cardiac output was measured during cardiac catheterization and prior to angiography. A Cournand catheter was positioned in the pulmonary artery and a 'pigtail' catheter in the descending aorta. The patient breathed room air via a two-way non-return breathing valve. An initial 5 min period of quiet breathing was allowed such that the patient became accustomed to mouthpiece breathing. This was followed by a further 5 min period of quiet breathing, during which expired air was collected in a Douglas bag. Expired volume was recorded using a Wright's respirometer (BOC). Arterial and mixed venous blood samples were drawn via the two catheters during the gas collection period at a rate of 1 ml min^{-1}. A further 5 ml of blood was drawn for the estimation of haemoglobin concentration. All measurements were made in the supine position with disturbance kept to a minimum. Heart rate (HR) was recorded at the end of the collection period.

The mixed expired air from the Douglas bag was analysed for oxygen and carbon dioxide using a mass spectrometer (V.G. Gas Analysis), which had been calibrated using known standards. Oxygen saturations from the blood samples were estimated using an oximeter (American Optical).

The repeatability of the direct Fick method was assessed by making duplicate collections of expired air and blood samples in a subgroup of patients.

Patient data were excluded from the study if something was known to have gone wrong with the measurement. Reasons for exclusion included (1) leakage of air from around the mouthpiece, (2) problems with the blood sampling, (3) patients who became excessively agitated, and (4) instrument malfunction. Data was not excluded on the basis of an unusual result either for oxygen consumption or cardiac output.

Oxygen consumption (ml min^{-1}) was calculated using the equation

$$\dot{V}O_2 = \dot{V}_E\,[(0{\cdot}2648 \times FE, N_2) - FE, O_2]\,1000$$

where: $\dot{V}_E$ is the average expired volume per minute corrected to STPD; FE, N_2 and FE, O_2 are the fractional expired nitrogen and oxygen concentrations, respectively; and 0·2648 corrects for the difference between the inspired and expired volumes.

The respiratory quotient (RQ), taken to be equivalent to the respiratory exchange ratio under steady-state conditions, was calculated using the equation

$$RQ = FE, CO_2/[(0{\cdot}2648 \times FE, N_2) - FE, O_2]$$

where FE, CO_2 is the fractional expired carbon dioxide concentration. A full derivation of these equations is given in Cotes[7].

Cardiac output was calculated according to the Fick equation[1]. Oxygen content (C, O_2) was calculated from the saturation using the equation

$$C{,}O_2 = (1{\cdot}39 \times S{,}O_2 \times Hb)/100\ mg(100\ ml)^{-1}$$

where S, O_2 is the oxygen saturation, Hb is the haemoglobin in mg $(100\ ml)^{-1}$ and 1·39 is the volume (ml) of oxygen carried by 1·0 g of haemoglobin and transported by the plasma. Oxygen consumption and cardiac output were indexed using the calculated BSA for each patient.

ASSUMED VALUES

The assumed values used by the various laboratories from which completed questionnaires were received was obtained from four basal metabolic rate studies[2–5], the data being given in tabular form based on age and sex. To provide the most accurate oxygen consumption values possible, the data set was converted from kcal $h^{-1}\,m^{-2}$ body surface area to ml min^{-1} oxygen m^{-2} body surface area. From the information provided by the questionnaires, it was apparent that a RQ value of 0·82 had been used to convert the basal metabolic rate to oxygen consumption. Thus, for each subject, the estimated oxygen consumption per square metre body surface area ($\dot{V}O_2$/BSA) was calculated from

$$\dot{V}O_2/BSA = (A \times 1000)/60 \times 4{\cdot}825)\ ml\,min^{-1}\,m^{-2}$$

where A is the calorie consumption per square metre per hour for a given age and sex, 1000 converts 1 min^{-1} to ml min^{-1}, 60 converts hours to minutes and 4·825 is the calories per litre of oxygen for an RQ of 0·82[8].

A further set of data, from the work of LaFarge and Miettinen[9], was also included. Although not used by any of the centres who replied to the questionnaire, the study on 879 patients is the largest collected during cardiac catheterization, and is considered by some to be the definitive work[10]. The $\dot{V}O_2$/BSA was calculated using the equations

Table 1 Anthropometric and haemodynamic data

	Males $n=50$	Females $n=30$
Age (years)	56.7 ± 8.0	61.4 ± 6.65
Height (m)	1.78 ± 0.06	1.62 ± 0.05
Mass (kg)	76.1 ± 11.52	62.9 ± 10.83
BSA (m^2)	1.91 ± 0.15	1.66 ± 0.14
HR (beats min^{-1}	72.5 ± 16.8	73.4 ± 18.2
RQ	0.92 ± 0.15	0.85 ± 0.18
$\dot{V}O_2$/BSA (ml min^{-1} m^{-2})	123.0 ± 27.5	116.7 ± 32.0
CI (l min^{-1} m^2)	3.08 ± 1.28	3.07 ± 1.47

Data given as mean ± s.d.
BSA, body surface area; HR, heart rate, RQ, respiratory quotient; $\dot{V}O_2$/BSA, indexed oxygen consumption; CI, cardiac index.

Males
$$\dot{V}O_2/BSA = [138.1 - 11.49 \ln(age) + 0.378(HR)]$$

Females
$$\dot{V}O_2/BSA = [138.1 - 17.04 \ln(age) + 0.378(HR)]$$

where $\dot{V}O_2$/BSA is in ml min^{-1} and ln is the natural logarithm.

The CI was calculated for each subject by substituting the measured $\dot{V}O_2$/BSA with the assumed value.

DATA ANALYSIS

To compare the measured and assumed values of $\dot{V}O_2$/BSA, linear regression analysis was applied to the data and analysed using the method of Altman and Bland[11] for comparison of two methods of estimating the same quantity, as correlation coefficients may be inappropriate. With this method, the differences between pairs of measurements are studied; a histogram of differences gives an indication of the statistical distribution and a plot of differences against mean values permits assessment of error and bias throughout the range studied. A paired *t*-test on the mean of observed differences, as compared with a mean of zero, gives a value of the probability of inherent bias in one method as compared with the standard.

The repeatability of the direct Fick method was assessed by calculating the standard deviation of the difference between duplicate measures of $\dot{V}O_2$ arteriovenous content difference, and cardiac output. The coefficient of repeatability[12] was then calculated as twice the standard deviation of the difference.

To assess the size of the error in CI using the assumed values, the percentage differences were calculated as (measured-assumed)/measured values.

Results

Ninety patients were studied, of which eighty (age range 38–78 years) provided satisfactory data. The anthropometric data, resting heart rate, respiratory quotient, indexed oxygen consumption and cardiac output for males and females is given in Table1. The mean RQ and HR values for the group were 0.89 ± 0.16 (range 0.65–1.22) and 73.2 ± 17.4 (range 44–120) beats min^{-1}, respectively. Five patients had a resting tachycardia (HR < 100 beats min^{-1}).

REPEATABILITY

The repeatability of the direct Fick method was assessed in nine patients. The mean and range of $\dot{V}O_2$, arteriovenous content difference and cardiac output for the duplicate studies are shown in Table 2. The coefficients of repeatability for $\dot{V}O_2$, arteriovenous oxygen content difference and cardiac output were, 53.26 ml min^{-1}, 1.16 ml per 100 ml and 0.72 l min^{-1}, respectively.

Table 2 Repeatability studies of direct Fick cardiac output

	Measurement 1	Measurement 2	Difference (1 − 2)
$\dot{V}O_2$ (ml min^{-1})	235.6 ± 50.2 (162 − 335)	246.9 ± 48.3 (157 − 317)	-11.3 ± 25.56 (−65 − 18)
$C(a\text{–}v)O_2$ (ml per 100 ml)	3.77 ± 0.68 (3.03 − 5.25)	3.79 ± 1.11 (2.81 − 6.51)	-0.024 ± 0.61 (−1.26 − 0.75)
CO (l min^{-1}	6.40 ± 1.54 (3.84 − 8.80)	6.77 ± 1.64 (4.10 − 0.87)	-0.37 ± 0.52 (−1.07 − 0.50)

Data given as mean ± s.d. with range in parentheses.

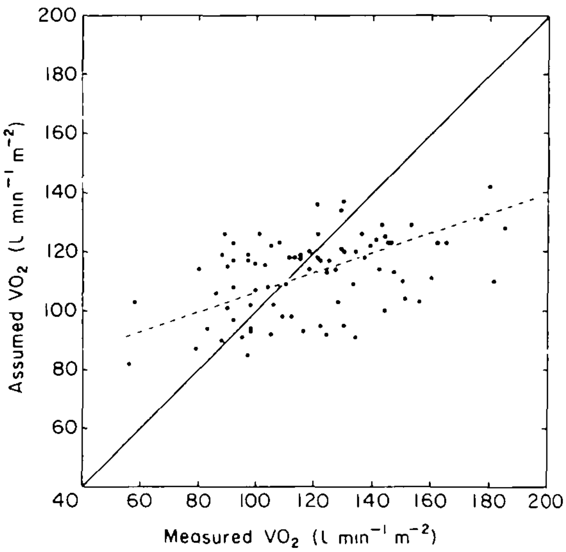

Figure 1 Relationship between measured indexed oxygen consumption ($\dot{V}O_2$) and assumed values from LaFarge and Miettinen. ———, Identity; – – – –, relationship.

INDEXED OXYGEN CONSUMPTION

Comparison of the measured data and assumed values using linear regression analysis revealed a significant relationship ($P<0.001$) with LaFarge and Miettinen data, but not with any of the other studies selected (Fig. 1). Generally, the higher values of $\dot{V}O_2$/BSA were underestimated, whilst the lower values were overestimated.

Analysis of the data using the method of Altman and Bland is summarized in Table 3. The error (indicated by the standard deviation) was similar for each set of assumed values. The relative bias (indicated by the mean of the differences) was lowest for the data of LaFarge and Miettinen[9] and highest for the data of Boothby *et al.*[2].

The mean $\dot{V}O_2$/BSA values and the distribution of the percentage differences are given in Table 4. Over half the assumed values were different by more than ±10%, of which many were different by more than ±25%. Agreement with measured values was closest for the equations of LaFarge and Miettinen[9] (Table 4).

Table 3 Summary of statistics on differences between measured and assumed values of $\dot{V}O_2$/BSA

	Robertson and Reid[3]	Boothby *et al*[2]	LaFarge and Miettinen[9]	Fleisch[4]	Aub and Dubois[5]
n	80	80	80	80	80
Mean	7·89	10·08	− 0·44	2·62	28·84
s.d.	29 2	28·2	29·0	28·9	28·8
Range	−57·1–116·6	−55·9–111·4	−65·8–109·7	−55–110·8	−70·9–103 9
SEM	3·27	3·15	3 24	3·23	2·22
95% CI	1·29–14·1	3·80–16·36	−6·9–6·02	−3·82–9·05	−10·8–2·04
P	0·018	0·89	0·002	0·42	0·18

Data is presented as mean, range, standard deviation (s.d.), standard error of mean (SEM) and 95% confidence intervals for the differences between measured and assumed values of $\dot{V}O_2$/BSA.
P values indicate the probability of inherent bias of the assumed method compared to the standard: values calculated as *t*-test of difference, mean = 0.

Table 4 Mean indexed oxygen consumption ($\dot{V}O_2$/BSA) values for assumed and measured values and the range of discrepancy between measured and assumed values

Source	Mean $\dot{V}O_2$/BSA ± 1 s.d. (ml min^{-1} m^{-2}) *n* = 80	Difference between measured and assumed values (No. of subjects)			
		±0–10%	±10–25%	±25–50%	> ±50%
Measured	120·6 ± 29·3	—	—	—	—
Boothby et al.[2]	10·7 ± 9·1	25	27	23	5
Robertson and Reid[3]	112·6 ± 4·9	27	26	23	4
Fleisch[4]	118·0 ± 4·8	29	26	21	4
Aub and Dubois[5]	129·0 ± 5·8	25	27	23	5
LaFarge and Miettinen[9]	121·7 ± 13·1	33	34	11	2

Table 5 Mean cardiac index (CI) values for assumed and measured values and the range of discrepancy between measured and assumed values

Source	Mean CI ± 1 s.d. ($l\ min^{-1}\ m^{-2}$) $n=80$	Difference between measured and assumed values (No. of subjects)			
		±0–10%	±10–25%	±25–50%	>±50%
Measured	3·05 ± 1·4	—	—	—	—
Boothby et al.[2]	2·79 ± 1·1	27	28	22	3
Robertson and Reid[3]	2·85 ± 1·1	28	25	23	4
Fleisch[4]	2·95 ± 1 1	26	29	21	4
Aub and Dubois[5]	3·27 ± 1·2	25	27	23	5
LaFarge and Miettinen[9]	3·07 ± 1·2	33	25	20	2

CARDIAC INDEX

The mean CI values and the distribution of the percentage differences are given in Table 5. As for $\dot{V}O_2$/BSA, over half the CI values were different by more than ±10% and many were more than ±25% different from the measured values. Again, closest agreement was obtained when comparison was made with the equations of LaFarge and Miettinen[9].

Discussion

The measurement of cardiac output is important in the assessment of ventricular function and shunt ratio, and a necessity for calculating vascular resistance. Of the many methods available, the direct Fick and the indicator dilution methods are the established standard techniques for the measurement of cardiac output because of their accuracy, safety, reproducibility and relative simplicity.

The direct Fick method requires steady-state sampling of arterial and mixed venous blood for oxygen contents and estimation of oxygen consumption. The practical and theoretical errors of the technique have been reviewed by Harris and Heath[13]. Blood sampling can lead to inaccuracies, particularly if the cardiac output is high. The error in estimating the arteriovenous oxygen difference is approximately 5%. However, the measurement of $\dot{V}O_2$ is usually the major source of error, the average error being approximately 6%[14].

Oxygen consumption should be measured during a quasi-steady state, where the rate of consumption of oxygen measured at the mouth should be the same as that in the alveolar capillaries. A collection period of at least 3 min is required to obtain an acceptable $\dot{V}O_2$ at rest[10].

Collection of expired air requires the patient to breath via a mouthpiece with the nose clipped; this is known to disturb the pattern and rate of breathing[15] and therefore it is necessary to allow the patient to become accustomed to this form of breathing prior to the gas collection, or alternatively, to use a hood system. However, some patients may find the latter somewhat claustrophobic. Overall the total error in the measurement of cardiac output by this method is approximately 10%[14]. In the present study, the direct Fick procedure had a coefficient of repeatability of 0·72 $l\ min^{-1}$, which is within the expected variation. The principal variant in the measurement was the estimation of $\dot{V}O_2$.

Due to these and other difficulties[13], it has become accepted practice to ascertain the arterial and mixed venous oxygen contents from direct measurements, and then to substitute an assumed $\dot{V}O_2$/BSA value into the Fick equation. Judging from the questionaire, the assumed values used in the U.K. are usually, if not exclusively, derived from the normal ranges of different basal metabolic rate studies[2–5]. The basal metabolic rate has been related to the age and sex of the subjects, and in the case of Fleisch[4] the data is an average of several different standards. This led us to question the use of these standards.

During cardiac catheterization, the subjects cannot be regarded as being in a truly 'basal' state. If they are sedated, both $\dot{V}O_2$ and HR usually decrease[16], and if unsedated, the patients may become agitated resulting in increased minute ventilation and HR. None of the patients studied was sedated, and a number were noted to have a high resting HR, with five having a resting tachycardia. LaFarge and Miettinon[9] recognized this and pointed out that the use of age alone is probably insufficient in the prediction of $\dot{V}O_2$/BSA. Their data, derived from measurements made during cardiac catheterization of semi-sedated patients, related $\dot{V}O_2$/BSA to age, sex and HR, which they found to be the most important determinants. Unfortunately, their data do no extend beyond the age of 40 years for men and 50 years for women, and therefore its application beyond these ages requires extrapolation, which in practice may not valid.

In this study, we have compared directly measured $\dot{V}O_2$/BSA with the assumed values[2–5,9]. In converting the data from the units of basal metabolic rate (kcal h^{-1} m^{-2}) to those for $\dot{V}O_2$/BSA (ml min^{-1} m^{-2}), an average value of 0·82 was used for RQ, the value chosen by all the centres. From our data, this could lead to large errors in the assumed $\dot{V}O_2$/BSA value. The range of RQ obtained (0·65–1·22) is quite wide, reflecting the difficulty in always maintaining, or even achieving, a steady state. Twelve patients (15%) had an RQ in excess of 1·0, despite completely satisfying the inclusion criteria. This wide range of RQ would give equivalent kilocalories per litre of oxygen ranging from 4·615 to 5·318 instead of the 4·825 (RQ = 0·82) used. This may account for some of the large discrepancies seen between measured and assumed values.

LaFarge and Miettinen[9] also used an assumed value for RQ (0·8) in their calculations. They found this to be acceptable, a judgement based on a subgroup of 56 (6%) of their patients. The majority of our patients were older than those in their study, but, despite this, their assumed values showed the closest agreement with the measured data (Table 5).

The CI values obtained using the assumed values showed a wide degree of variation. In all cases, the majority of values differed from the measured value by more than ±10%, and some by more than ±50%.

In conclusion, the use of assumed oxygen consumption values can lead to quite substantial errors in the estimation of cardiac output and CI. This, in turn, will result in substantial errors in the calculation of resistance and valve area. Therefore, where possible, expired gases should be collected and analysed. Assumed values should only be used when this measurement is unobtainable, and then with caution, and particularly so when the patient is not in a basal state. The equations of LaFarge and Miettinen[47] gave the closest approximation to measured oxygen consumption, despite the fact that none of their patients were as old as those included in our study.

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