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Modification of Fick's Principle for the Determination of Relative Shunts

By

K. Lozsádi

Department of Surgery, National Institute of Cardiology, Budapest

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Fick's formulae [1] are widely used for the determination of cardiac output in respect of both the systemic and the pulmonary circulation. The quotient in which O_2 uptake per minute is the numerator and the difference between O_2 tension in the aorta and that in the venae cavae the denominator, serves to determine the absolute value (with an error of ± 3 per cent) of the circulating blood volume per minute. The analogous quotient for the pulmonary circulation contains the same numerator, and the difference between the O_2 tension in the pulmonary vein and that in the pulmonary artery as denominator *(Fick's direct principle)*.

The method's range of application has been extended by *Fick's indirect principle* which substitutes the volume of expired CO_2 for that of O_2 uptake.

It is not always necessary to determine the exact value of systemic and pulmonary cardiac output: the ratio of the two values will usually suffice in cardiological practice since, in cases of shunt, it indicates the percentual elevation of the output in one of the two circulations in relation to the output in the other.

Method

It is supposed that, when applying Fick's direct principle, the determination of both systemic and pulmonary cardiac output is based on the same O_2 uptake per minute.

Cardiac output in respect of the systemic circulation is $(N) = \dfrac{O_2}{A_{a0} - V_c} \times 100$ where O_2 means O_2 uptake per minute in ml, A_{a0} the oxygen content of aortic blood in volume per 100 ml and V_c the average O_2 content of blood in the venae cavae, likewise in volume per 100 ml. Supposing that, under normal conditions, cardiac output (δ) is equal in the systemic and the pulmonary (K) circulation

$$K = \frac{O_2}{V_p - A_p} \cdot 100, \text{ i. e. } N = K$$

where V_p means O_2 saturation in the pulmonary vein, and A_p that in the pulmonary artery, both in volume per 100 ml.

Let us take an example.

$O_2 = 200$ ml; V_p and $A_{a0} = 19$ vol; V_c and $A_p = 11$ vol. Therefore,

$$N = \frac{200}{19 - 11} \cdot 100 \text{ and}$$

$$K = \frac{200}{19 - 11} \cdot 100 \text{ which}$$

means that cardiac output is 2500 ml in both cases, their quotient $\left(\frac{2500}{2500}\right)$ being the unit. The formula can, of course, be simplified by omitting the factor 100. Another simplification can be made if we divide by O_2.

$$N = \frac{O_2}{\frac{A_{a0} - V_c}{O_2}} \text{ and } K = \frac{O_2}{\frac{V_p - A_p}{O_2}}, \text{ i.e.}$$

$$N = \frac{O_2}{(A_{a0} - V_c) \cdot O_2} = \frac{1}{(A_{a0} - V_c) \cdot 1} = \frac{1}{A_{a0} - V_c}$$

and

$$K = \frac{O_2}{(V_p - A_p) \cdot O_2} = \frac{1}{(V_p - A_p) \cdot 1} = \frac{1}{V_p - A_p},$$

so that the ratios $\frac{N}{K} =$

$$= \frac{\frac{1}{A_{a0} - V_c}}{\frac{1}{V_p - A_p}} = \frac{V_p - A_p}{A_{a0} - V_c} \text{ and}$$

$$\frac{K}{N} = \frac{\frac{1}{V_p - A_p}}{\frac{1}{A_{a0} - V_c}} = \frac{A_{a0} - V_c}{V_p - A_p}$$

remain unchanged.

Substituting now the values of the foregoing example we have $\frac{N}{K} = \frac{K}{N} = \frac{19 - 11}{19 - 11} = 1$. With the aid of the above formulas, derived from those of Fick, it is possible to compute the ratio between the respective cardiac outputs of the systemic and pulmonary circulation from the blood O_2 values alone, without having to measure the volume of O_2 uptake or CO_2 output. The ratio shows how many times cardiac output of the one side is higher than that of the other. (For example, in a case of left-to-right shunt, how many times the cardiac output of the right heart is higher than that of the left).

We have suggested the term "*Fick's simplified principle*" for this method.

Left-to-right shunt (S_{1-r}). Cardiac output for the pulmonary circulation exceeds that of the systemic. The quotient $\frac{K}{N}$ expresses the magnitude of the shunt in relation to the cardiac output for systemic circulation.

$$S_{1-r} = \frac{K}{N} = \frac{A_{a0} - V_c}{V_p - A_p}.$$

If, for example, $A_{a0} = 19$ vol, $V_p = 19$ vol, $V_c = 11$ vol, and $A_p = 15$ vol.

$S_{1-r} = \frac{19 - 11}{19 - 15} = 2$, i.e. cardiac output for the pulmonary circulation is twice that of the systemic one.

Right-to-left shunt (S_{r-1}). It will now be the cardiac output of systemic circulation which exceeds that of the pulmonary circulation and the quotient $\frac{N}{K}$ expresses the magnitude of the shunt in relation to the cardiac output for the pulmonary circulation.

$$S_{r-1} = \frac{V_p - A_p}{A_{a0} - V_c}.$$

If, for example, $A_{a0} = 16$ vol, $V_p = 19$ vol, $V_c = 10$ vol, and $A_p = 10$ vol.

$S_{r-1} = \dfrac{19 - 10}{16 - 10} = 1.5$, i.e. cardiac output for systemic circulation is 50 per cent higher than that for the pulmonary.

To sum up, in cases of left-to-right shunt to arterio-venous O_2 difference of the pulmonary circulation is brought into relation with the O_2 difference of systemic circulation, while the numerator and denominator change places in cases of right-to left shunt.

Two-way shunts. In such cases cardiac output for both systemic and pulmonary circulation is elevated. The extent of the left-to-right shunt depends on the excess volume of blood streaming in at some point of the segment between the venae cavae and the pulmonary artery which is added to the flow in the venae cavae. Cardiac output for the pulmonary circulation is, thus, composed of the volume of blood arriving through the venae cavae $\left(\dfrac{O_2}{V_p - V_c}\right)$ and the volume of shunted blood $\left(\dfrac{O_2}{A_p - V_c}\right)$. The relation of the latter ($Q_{k/s}$) to systemic circulation cardiac output can be computed from the formula $Q_{k/s} = \dfrac{\dfrac{O_2}{V_p - V_c}}{\dfrac{O_2}{A_p - V_c}}$. Applying now Fick's simplified principle we obtain

$$Q_{k/s} = \frac{A_p - V_c}{V_p - V_c}.$$

If, for example, $A_{a0} = 18$ vol%, $V_p = 20$ vol%, $V_c = 10$ vol% and $A_p = 12$ vol%, we have $Q_{k/s} = \dfrac{12 - 10}{20 - 10} = 0.2$ which means that 20 per cent of the cardiac output of the pulmonary circulation is contributed by the left-to-right shunt.

Right-to-left shunt represents the volume of blood which does not traverse the lung but increases systemic cardiac output. To the volume of blood arriving from the pulmonary veins $\left(\text{i.e. cardiac output for the pulmonary circulation} = \dfrac{O}{V_p - A_p}\right)$ is added the volume of shunted blood $\left(Q_{n/s} = \dfrac{O_2}{V_p - A_{a0}}\right)$ which corresponds to $\dfrac{\dfrac{O_2}{V_p - A_p}}{\dfrac{O_2}{V_p - V_{a0}}}$ per cent of the original systemic cardiac output. Applying now Fick's simplified principle, we obtain $Q_{n/s} = \dfrac{V_p - A_{a0}}{V_p - A_p}$. Substituting the values of the foregoing example, we have $Q_{n/s} = \dfrac{20 - 18}{20 - 12} = 0.25$ which means that 25 per cent of the systemic cardiac output is contributed by the right-to-left shunt.

The ratio of $Q_{k/s}$ and $Q_{n/s}$ shows whether the left-to-right or the right-to-left shunt is predominant in a case of two-way shunt:

$$S_d = \frac{Q_{k/s}}{Q_{n/s}}.$$

In the above example, $S_d = \frac{0.2}{0.25} = 0.8$ which means that the right-to-left exceeds the left-to-right shunt by 20 per cent.

The simplified method yields more precise results than either the direct or the indirect formulae of Fick because it eliminates a factor (O_2 uptake or CO_2 output) and contains, thus, fewer sources of error.

The application of Fick's simplified principles in cases of congenital heart disease will be discussed separately.

Summary

Fick's formulae are widely used for the determination of cardiac output of the right and the left heart. Knowledge of the absolute values is rarely necessary since their ratio suffices in most cases. As congenital heart disease has usually to be diagnosed in children, exact measurement of the volume of oxygen inspired per minute — as required by Fick's method — is difficult. Determination of the cardiac outputs for systemic and pulmonary circulation is based on the same oxygen uptake per minute. Therefore, a comparison of the corresponding arterio-venous oxygen values allows the determination of the ratio between the two cardiac outputs without having to ascertain the volume of oxygen inspired per unit of time.

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Dr. K. Lozsádi
Nagyvárad tér 1.
Budapest IX., Hungary