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Special Article

Calculating Vascular Resistances

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Summary: Vascular resistance calculations often affect decisions regarding therapeutic options encountered by physicians and their patients. However, many of the terms, units, and methods used when calculating vascular resistances are ambiguous. This report attempts to clarify some of these ambiguities and suggests methods for predicting normal vascular resistances.

Key words: pulmonary, systemic, vascular resistance, blood flow, terminology, units, calculations

Introduction

Pulmonary and systemic vascular resistance calculations are used by physicians to guide numerous medical decisions. For example, these calculations may influence the initiation, titration, and discontinuation of vasodilator therapy, and may even play a pivotal role in some critical medical decisions. Judgments pertaining to life-sustaining therapies, such as those encountered during the rationing of heart transplants, hinge upon vascular resistance calculations. They weigh heavily in the determination of "candidacy" for corrective congenital heart surgery and can sway decisions to withdraw life-sustaining medical support of critically ill people. When calculating vascular resistances to facilitate medical reasoning, physicians should recognize the importance of using clear terminology, unambiguous expressions of units, and valid calculation methods. We find that many of the terms, units, and methods associated with vascular resistance calculations remain unclear in the medical literature; in this report, we attempt to highlight and clarify some of them.

Terminology Derivation, Definition, and Deviation

The German physicist George Simon Ohm (1787–1854) discovered that electric potential (voltage) differences (ΔV) and flows of current (I) between two sites of metallic conductors are linearly related. The linearity of this relationship between potential difference and current (rather than either equation shown below) characterizes Ohm's law.[1] Hydraulic resistances of vascular beds (vascular conductors) are determined using an analogy to electric resistances of metallic conductors. Metallic conductors, unlike many other conductors of current such as vacuum tubes and transistors, are used in the analogy because they generally obey Ohm's law. Both electric and hydraulic conductors are considered to obey Ohm's law if their potential differences are linearly related to their flows. In other words, conductors of both types obey Ohm's law if their resistances are constant and thereby independent of changes in potential differences and flow.

As shown in the following equation, the ratio of ΔV to I has been adapted as the definition of electric resistance (R_{elec}) for conductors of current.

$$R_{elec} = \Delta V/I$$

Similarly, the ratio of an hydraulic potential (pressure) difference (ΔP) to blood flow (Q) has been adapted as the definition of vascular resistance (R_{vasc}) for conductors of blood.

$$R_{vasc} = \Delta P/Q$$

Therefore, either equation can be used to calculate resistance(s) of a conductor whether or not the employed conductor obeys Ohm's law. Several features of blood flow (such as viscosity, vascular distensibility, pulse wave reflections, and fluid turbulence) confound the obeyance of vascular conductors with Ohm's law, yet the extent to which ignoring these features affects critical medical judgments is unclear.[2, 3]

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The terms ascribed to measurements and calculations associated with hydraulic conductors generally adhere to the electronics analogy. Deviation from this analogy can cause confusion. Consider the term "total vascular resistance." This resistance calculation has been defined, in reference to both pulmonary and systemic calculations, as the ratio of mean arterial pressure to mean blood flow. Because the definition omits venous pressure, the resulting values are unrelated to hydraulic potential differences. This concept of "total vascular resistance" has no analogy in the field of electronics. Those individuals who feel compelled to use the ratio of arterial pressure to blood flow without incorporating a measurement of venous pressure should refer to the resulting value as something other than a resistance calculation. Otherwise, the impression that these calculations characterize or pertain to particular conductors is wrongfully conveyed.

Expressions of Units

Some confusion regarding vascular resistance calculations has evolved simply from imprecise reporting. As an example, consider the popular method of reporting vascular resistance units as "mmHg/l/min." Those who are familiar with programming calculators or entering formulae into spreadsheet programs will quickly recognize the ambiguity of mathematical operation precedence in the formula described by these units. If not specified otherwise, mathematical operators are generally used in formulae as they are encountered from left to right. Regarding calculations of vascular resistance, acceptance of the aforementioned definition of vascular resistance validates the idea that volume should be divided by time as the first mathematical operation (as opposed to dividing the pressure difference by a volume first and then dividing the resulting value by time), thus suggesting an inconsistency between this expression of vascular resistance units and the method of calculating vascular resistance.

Generally, mathematical operation precedence is not confused during calculation of vascular resistances because flow estimates are either impulsively or automatically calculated first. However, mathematical operation precedence becomes extraordinarily ambiguous when indexed vascular resistances are reported as "mmHg/l/min/m^2." This expression of units is not obviously translatable and is contributing to vast inconsistencies in calculations of indexed vascular resistances. The formula implicit in the expression "mmHg/l/min/m^2" can be viewed as either a pressure difference divided by an indexed flow [the ratio of cardiac output to body surface area (BSA)] or a resistance calculation divided by BSA. The resulting values are dramatically different (Fig. 1); however, neither method is consistently reported in the medical literature. Furthermore, neither method adheres to a left-to-right precedence order. When investigators report vascular resistance calculations that have been indexed to BSA, they might find that expressing vascular resistance units using exponents will avoid ambiguity (i.e., mmHg$\cdot$l$^{-1}\cdot$min$\cdot$m^2 or mmHg$\cdot$l$^{-1}\cdot$min$\cdot$m^{-2}).

$$\begin{array}{c}2\\1\end{array}\;\frac{\Delta P}{\dfrac{Q}{\mathrm{BSA}}} = \frac{18}{\dfrac{6}{2}} = \frac{18}{3} = 6 \quad \mathrm{mmHg}\cdot\mathrm{l}^{-1}\cdot\mathrm{min}\cdot\mathrm{m}^2$$

$$\begin{array}{c}1\\2\end{array}\;\frac{\dfrac{\Delta P}{Q}}{\mathrm{BSA}} = \frac{\dfrac{18}{6}}{2} = \frac{3}{2} = 1.5 \quad \mathrm{mmHg}\cdot\mathrm{l}^{-1}\cdot\mathrm{min}\cdot\mathrm{m}^2$$

FIG. 1 Effect of mathematical operation order. Δ = Potential (pressure) difference, Q = blood flow, BSA = body surface area.

Vascular Resistance Indexing Methods

Published medical literature contains many indices that involve dividing hemodynamic values by morphometric or chronological indicators. For reasons similar to those suggesting that meaningful compliance with Ohm's law necessitates the existence of direct linear relationships between electric potential differences and flow, meaningful use of hemodynamic indices necessitates the existence of direct linear relationships between the hemodynamic values and their indicators. In adulthood, pulmonary and systemic vascular resistances increase roughly linearly with age.[4–6] In childhood, however, these resistances decrease with age, albeit in a nonlinear manner.[7] Because BSA generally increases during childhood, vascular resistances should be expected to relate roughly directly to the inverse of BSA estimates—at least in children. Thus, if direct linear indexing to BSA is desired, then the most appropriate method of calculating the index is to divide vascular resistance by the inverse of BSA. This mathematical operation is equivalent to both multiplying vascular resistance by BSA and dividing the hydraulic potential (pressure) difference by cardiac index. In either case, enforcing linearity of the relationship between vascular resistance and BSA most appropriately yields the units "mmHg$\cdot$l$^{-1}\cdot$min$\cdot$m^2."

The validity of using BSA as an indicator for calculations of hemodynamic indices has been challenged by several investigators.[8–12] Recall that estimates of BSA are generally determined from multiple regression-based formulae using height (in cm) and mass (in kg). Using height and mass in a multiple regression-based formula (to calculate BSA) and then using the resultant estimate of BSA in a linear regression-based formula (to calculate an index) seems redundant. Some investigators argue that this redundancy inadvertently amplifies imprecision of hemodynamic indices. Using the cardiac (output) index as an illustrative example, Krovetz and Goldbloom demonstrated the fallacy of using BSA estimates to create hemodynamic indices. Using 115 normal subjects from 1 month to 20 years of age, they showed that linear correlations of cardiac output with either height or mass alone were higher than those with estimates of BSA (which were derived from the height and mass measurements).[8]

The fact that the cardiac (output) index changes during childhood and adulthood[10, 11] serves as another compelling argument against using BSA as an indicator for calculations of hemodynamic indices. The mere existence of a relationship between the cardiac index and age seems to confound the purpose of indexing the cardiac output. In childhood, normal vascular resistance changes occur predominantly as a result of cardiac output changes rather than a result of the hydraulic potential (pressure) differences changes.[7] At least in childhood, therefore, one should expect vascular resistances that are indexed using BSA to vary with age. If this expectation is true, then the purpose of indexing vascular resistance would seem to be lost.

Interpreting Vascular Resistance Calculations

The process of a vascular resistance calculation influencing a medical decision usually begins with a physician suspecting that a patient might have an abnormal vascular conductor (vascular bed). Mean arterial hydraulic pressure, mean venous hydraulic pressure, and mean blood flow are then measured. After calculating vascular resistance, the physician usually tries to decide whether the value is normal or abnormal. Nearly always when this value is believed to be abnormal, and sometimes when it is believed to be normal, will the physician desire a sense of how much the value deviates from the predicted mean normal value. Then the physician will usually search for scientifically studied algorithms that could help guide decisions regarding medical therapies. Rarely, if ever, are any available algorithms so refined that individual vascular resistance calculations effect automatic medical decisions. Making value judgments regarding the relative significance of all available data pertaining to an individual patient and simultaneously choosing an applicable, scientifically justified algorithm is, at present, a necessary art in medicine.

For the physician to develop a sense of whether or not a patient's vascular resistances are normal or abnormal, confidence boundaries that define upper and lower normal limits are desirable. We are unaware of published regression-based formulae that can be used to determine upper and lower confidence boundaries for normal vascular resistances of populations of various ages and sizes. We are aware, however, of some regression equations that can be used to predict mean normal vascular resistances[4, 6, 8] (Table I). By using these regression equations, one can at least develop some sense of how much individual vascular resistances deviate from calculated mean normal values. In an effort to compare values of an individual with those of the normal population, one might, as an example, calculate the ratio of the individual's value to the predicted mean normal value. Because we aim to appreciate individual vascular resistance calculations independent of age and size, mean normal values used for comparison probably should be calculated using regression-based formulae that include age, height, and/or mass as variables.

The ratio of pulmonary to systemic vascular resistance is another useful calculation. It is interesting to note that from 1 month to 20 years of age, the pulmonary and systemic mean pressures remain fairly constant (around 12 mmHg and 84 mmHg, respectively).[7] Because the pulmonary and systemic circuits are normally arranged in series rather than parallel, one can assume that pulmonary blood flow closely resembles systemic blood flow in the normal population. Therefore, the pulmonary-to-systemic resistance ratio should also be expected to remain fairly constant (around 14%)—at least from 1 month to 20 years of age. Calculated vascular resistance ratios of normal children have been shown to follow this expectation.[7]

Conclusions and Recommendations

Although any method of comparing individual with normal resistance calculations will necessarily be imperfect, we believe that physicians should strive for perfection, particularly when the outcome of their efforts sway pivotal decisions regarding the lives of others. Physicians should feel obligated to use clear terminology, unambiguous expressions of units, and valid calculation methods. To aid those who use vascular resistance calculations, we encourage the development of regression-based formulae that can be used for cal-

TABLE I Formulae for calculating normal vascular resistances

	1 Month to 20 years		Over 20 years	
	PVR	SVR	PVR	SVR
Formula	$6.4\,(\text{age})^{-1} - 4.4\,(\text{age})^{-2} + 10.0\,(\text{height})^{-1} + 0.3$ [a]	$8.9\,(\text{age})^{-1} + 3064.2\,(\text{height})^{-1} - 10.8\,(\text{mass})^{-1} - 5.3$	$0.0252\,(\text{age}) + 0.138$ [b]	$0.122\,(\text{age}) + 10.7$ [b]
Authors (Ref. No.)	Krovetz and Goldbloom (7)	Krovetz and Goldbloom (7)	Davidson and Fee (4)	Nichols *et al.* (6)
No. of patients	62	94	47	45
R	0.53	0.93	0.69	0.47

[a] Ages less than 1 year are probably inappropriate for this equation.

[b] Formulae shown here have been modified from their original form so that values could be expressed in $\text{mmHg} \cdot \text{l}^{-1} \cdot \text{min}$.

Abbreviations: PVR = pulmonary vascular resistance in $\text{mmHg} \cdot \text{l}^{-1} \cdot \text{min}$, SVR = systemic vascular resistance in $\text{mmHg} \cdot \text{l}^{-1} \cdot \text{min}$, age units = years, height units = cm, mass units = kg, R = correlation coefficient.

culating both normal vascular resistance means and their confidence boundaries.

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