

Patient Directed Perfusion Pressure on Bypass, an Analogy from Electrical Engineering—A New Concept

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Abstract: Organ ischemia, particularly mesenteric and renal, can occur despite a seemingly adequate perfusion flow and pressure during a period of cardiopulmonary bypass. The blood pressure to run bypass at remains a contentious issue. We present the concept that perfusion pressure during cardiopulmonary bypass should be patient specific, depending on an individual's resting pre-procedural blood pressure. Four simulated arterial traces with variable morphology, but identical systolic and diastolic blood pressures, were analyzed to calculate the medical mean, arithmetic mean, and root mean square of the blood pressure tracing. Using the

standard medical formula for calculation of mean blood pressure, you can potentially underestimate perfusion pressure by 12 mmHg in a normotensive subject. The root mean square pressure calculates the equivalent non pulsatile pressure that will deliver the same hydraulic power to the circulation as its pulsatile equivalent. Patient specific perfusion pressures, calculated via root mean square may potentially help reduce the incidence of organ ischemia during cardiopulmonary bypass. Clinical trials are needed to confirm or refute this concept. **Keywords:** cardiopulmonary bypass, perfusion pressure. *JECT. 2010;42:57–60*

Organ ischemia, particularly mesenteric and renal, can occur despite a seemingly uneventful period of cardiopulmonary bypass (CPB), followed by adequate cardiac output and blood pressure in the post operative period. Four physical properties can partly explain this: inadequate blood flow, low perfusion pressure, reduced oxygen delivery (via low hematocrit), and the effects of the loss of pulsatility (1–6).

Total pump flow during CPB (calculated from body surface area) and hematocrit can both be controlled by the perfusionist. True pulsatile flow during CPB is not possible with current pump and cannulae technology.

Target blood pressure during CPB is highly controversial with little universal agreement (7–9). The cardiovascular system can be modeled by lumped element analysis, consisting of resistors, capacitors, and inductors (2), enabling

an analogy from electrical engineering to potentially partly unravel this clinical problem.

The DC (direct current, non pulsatile) equivalent voltage of an AC (alternating current, pulsatile) voltage to deliver the same power can be calculated via the term root mean square (RMS) (10). By analogy the non pulsatile equivalent blood pressure of a patient's pre-bypass blood pressure (pulsatile) can be calculated via the term root mean square to deliver the same hydraulic power. We sought to demonstrate that the RMS, medical mean and arithmetic mean vary depending on arterial waveform morphology.

METHODS

Calculation of Means

The means were calculated as follows:

$$\text{Medical mean} = \text{diastolic blood pressure} + 1/3 (\text{systolic blood pressure} - \text{diastolic blood pressure}) \quad (1)$$

$$\text{Arithmetic mean} = \frac{1}{n} \sum_{i=1}^n x_i = \frac{x_1 + x_2 + \dots + x_n}{n} \quad (2)$$

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RMS (11,10), (Appendix 1) =

$$\sqrt{\frac{1}{n} \sum_{i=1}^n x_i^2} = \sqrt{\frac{x_1^2 + x_2^2 + \dots + x_n^2}{n}} \quad (3)$$

where x_1, x_2, x_n are instantaneous arterial blood pressure readings.

The corresponding formula for a continuous function $f(t)$, e.g., blood pressure, defined over the interval $T_1 \leq t \leq T_2$ is:

$$\sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} [f(t)]^2 dt} \quad (4)$$

The RMS of a periodic function such as blood pressure is equal to the RMS of one period of the function, e.g., one cycle. The RMS value of a continuous function or signal can be approximated by taking the RMS value of a series of equally spaced samples. This would be the case for a patient's blood pressure due to natural physiological arterial swing.

Both the arithmetic mean and the RMS are special cases of the "power" (or generalized) mean:

$$\left(\frac{1}{n} \sum_{i=1}^n x_i^m \right)^{\frac{1}{m}} \quad (5)$$

where $m = 1$ for the arithmetic and $m = 2$ for the RMS. For example the "infinite" power mean ($m \rightarrow \infty$) returns the largest individual value (e.g., the systolic blood pressure).

Blood Pressure Traces

To demonstrate our concept, arterial traces with equal systolic and diastolic blood pressures but with different pulse waveform geometries were needed. Unfortunately the chances of finding patients with identical systolic and diastolic pressures is very low, so a previously recorded arterial trace was modified mathematically to produce four different waveform geometries but with identical systolic and diastolic pressures (11) (Figure 1).

Medical Equivalents of Electrical Formula

The electrical and medical equivalent formula for DC (non pulsatile) and AC (pulsatile) power delivery is shown in Table 1.

RESULTS

RMS

It can be seen from Table 2 that using the standard medical formula for calculation of mean blood pressure, perfusion pressure could potentially be underestimated by 12 mmHg (an error of about 15%) in a normotensive

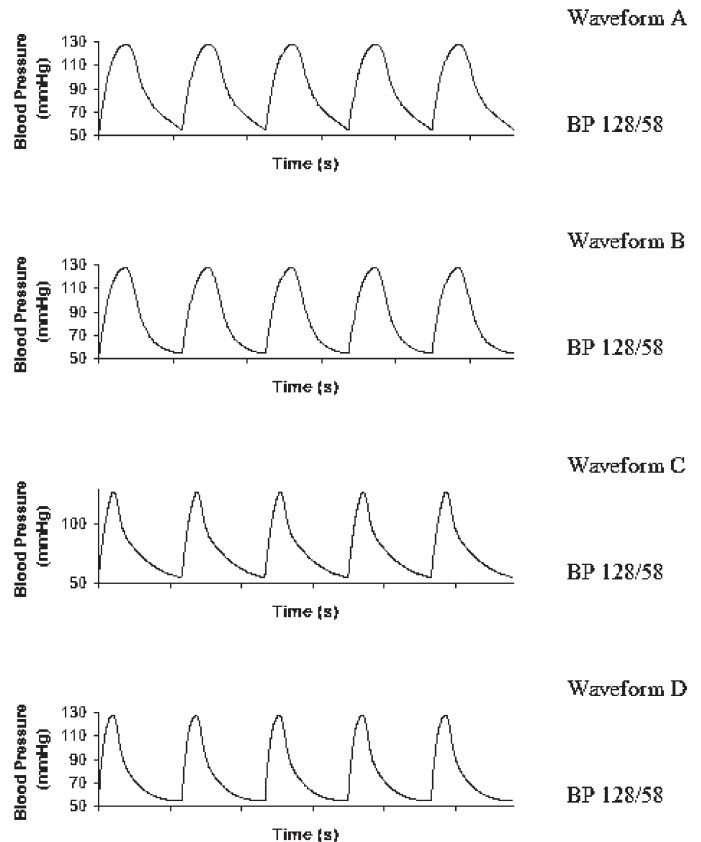


Figure 1. Four different arterial traces with identical diastolic and systolic pressures.

subject, if the medical mean was utilized as the reference point.

Arithmetic Mean

The arithmetic mean results demonstrated the biggest difference in predicted perfusion pressure, 14 mmHg.

DISCUSSION

From electrical circuit theory the equivalent non pulsatile pressure of perfusion should be the RMS value of their

Table 1. The electrical and medical equivalent formula for DC (non pulsatile) and AC (pulsatile) power.

	Electrical Formula	Medical Formula
Direct Current (DC) or Nonpulsatile	$V = I.R$ $Power = I.V$ $Power = V^2/R$	$BP = CO.SVR$ Power delivered by CPB = $CO.BP$ Power delivered by CPB = BP^2/SVR
Alternating Current (AC) or Pulsatile	$V_{RMS} = I_{RMS}.R$ $Power = I.V_{RMS}$ $Power = V_{RMS}^2/R$	$BP = CO.SVR$ Power delivered by heart = $CO.BP_{RMS}$ Power delivered by heart = BP_{RMS}^2/SVR

BP, blood pressure; CO, cardiac output; SVR, systemic vascular resistance; RMS, root mean square; I, current; R, resistance; V, voltage.

Table 2. Mean blood pressure as calculated by medical, arithmetic, geometric, and root mean square techniques.

	Mean Blood Pressure (mmHg)		
	Medical	Arithmetic	RMS
Waveform A	81	90	93
Waveform B	81	85	89
Waveform C	81	79	82
Waveform D	81	76	80

preoperative blood pressure. Assuming preoperative organ perfusion is adequate, so if pump flow and hematocrit are adequate during CPB, then if pulsatile flow is not necessary, the RMS of the preoperative blood pressure should be the target pressure on bypass.

If an adequate perfusion pressure is utilized then indirectly the effects of pulsatile flow can be evaluated and the true effects of inflammation and organ damage can be studied, without potentially blood pressure confounding the analysis. Indirectly, the use of an RMS directed perfusion pressure on bypass answers the question if pulsatile flow is better than non pulsatile flow; if ischemia occurs then with all other factors controlled, lack of pulsatility is the problem.

The concept of RMS equivalent voltage arose in electrical engineering because of the need to deliver an equivalent amount of electrical energy or power to electrical loads. It is intuitive, but unproven, that optimal tissue perfusion will occur if the bypass machine delivers the same amount of hydraulic energy/power to the patient as the heart does under resting conditions. If just the perfusion pressure is key then the arithmetic mean should be your perfusion pressure target. In either case the medical mean does not incorporate the shape of the arterial trace at all—failing to distinguish between the different shapes illustrated in Figure 1 for example.

The arithmetic mean represents the underlying DC value of a pulsatile waveform after Fourier analysis (12). Should the concept presented here be overly complicated and power delivery by the bypass machine be unimportant, then just the perfusion pressure based on the arithmetic mean should be your perfusion pressure target. This situation arises due to the fact that pressure is squared in the calculation of power. Finally, we note that the RMS value will always return a higher value than the arithmetic mean.

LIMITATIONS

Numerous factors were not included in this model: patient arterial compliance, the effect of isolated systolic hypertension, and the effect of pulse pressure not included.

In addition errors due to damping and resonance which will impact mostly the diastolic and systolic blood pressure were not accounted for. However, from the arithmetic mean formula 2 and the RMS formula 4, it can be seen that the error will be relatively equal as exactly the same terms are involved. The mean that will be very inaccurate in this situation is the medical mean, formula 1.

CONCLUSION

Matching perfusion pressure on bypass using the technique of root mean square, to the patient's pre-operative blood pressure may help to reduce organ ischemia and answer the question "what pressure to run bypass at." Clinical trials are needed to confirm or refute this concept.

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Appendix 1: Derivation of Root Mean Square

An analogy between medical and electrical formula exists allowing direct adoption of the following electrical formula directly in medical practice.

Power (P) delivered to an electrical circuit with resistance R, can be calculated from Equation A.

$$P = V^2/R \quad (A)$$

For a continuous voltage $F(t)$, where F is voltage at time t .
Power delivered at a time instant x , P_x , can be summed
up as:

$$P_x = 1/R * F_x^2$$

Total Power delivered can be summed from:

$$P = \sum_{n=0}^t \frac{F_n^2}{R}$$

which is the same as:

$$P = \frac{F_0^2 + F_1^2 + \dots + F_n^2}{R}$$

From Equation A, V can be equated to:

$$V_{RMS} = \sqrt{\frac{F_0^2 + F_1^2 + \dots + F_n^2}{R}}$$

Equation 3 in methods section. RMS subscript is added
as it describes the square root of the means of the squares.