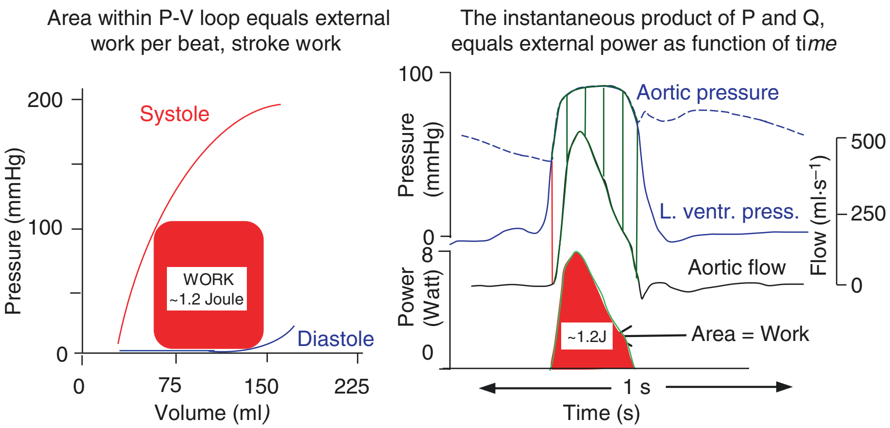
Chapter 16
Cardiac Work, Energy and Power



Left: External work per beat, stroke work, can be determined from the area contained in the pressure-volume loop, mmHg·ml or Joule, as first suggested by Frank [1]. Multiplication of stroke work by Heart Rate gives cardiac power (mmHg.ml/s or Watt). Right: External power (work per unit time) can be calculated from the instantaneous product of ventricular (or aortic) pressure, $P(t)$, and flow, $Q(t)$: Power = $P(t) \cdot Q(t)$, mmHg·ml·s^{-1} or Watt. The area under the power curve is stroke work mmHg·ml or Joule. The calculation of energy and power does not require a linear system, as, for example, in the calculation of resistance and impedance. This makes the use of energy and power very broadly applicable in hemodynamics. Power and work are a characterization of heart and load together, while the End-Systolic Pressure-Volume Relation and Pump Function Graph characterize the heart; resistance and impedance characterize the arterial system.

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16.1 Description

Work and the potential to do work, energy, are based on the product of force times displacement, the units being Newton times meter (Nm or Joule). When work is expressed per unit time it is power (Nm/s or Watt). In hemodynamics this translates to pressure times volume (Joule or mmHg·ml) and pressure times flow (watt or Joule or mmHg·ml/s), respectively. Linearity of the relations between pressure and volume or flow is not required in the calculation of work and power, while linearity is required in the calculation of resistance and input impedance. However, work and power depend on heart and load, while the ventricular pressure volume relation and the pump function graph describe the heart and vascular resistance describes the vascular system.

In the heart, external work can be derived from pressure and volume through the pressure-volume loop, as first suggested by Otto Frank in 1898 [1], it is the area contained within that loop. The so calculated work is, of course, the external work produced by the heart during that heartbeat and called work per beat or stroke work.

Power delivered by the heart to the arterial load equals the instantaneous pressure times flow (Figure in Box). Both pressure, P, and flow, Q, vary with time, and the instantaneous power, calculated as $P(t) \cdot Q(t)$ also varies with time. This means that instantaneous power varies over the heartbeat and is zero in diastole because aortic flow is zero. Thus, external work and power are only generated during ejection. Total energy is the integral of power, in mathematical form $\int P(t) \cdot Q(t)\, \mathrm{d}t$, the integral sign, $\int$, together with dt implies that at all moments in time pressure and flow values are multiplied and the products added. The integration is carried out over the heart period T, but since flow is zero in diastole (assuming patent valves) integration over the ejection period is adequate. The average power over the heart beat is $(1/T) \cdot \int P(t) \cdot Q(t) \cdot \mathrm{d}t$. Since aortic pressure and left ventricular pressure are practically equal during ejection, both ventricular pressure and aortic pressure may be used in the calculation.

Sometimes mean power is calculated as the product of mean pressure and mean flow (Cardiac Output). Here aortic pressure is to be used because it is the mean power delivered to the arterial system that we want to calculate. Since mean aortic pressure is about 2–3 times higher than mean left ventricular pressure, using ventricular pressure would lead to considerable errors [2]. The difference between total power and mean power $(1/T) \cdot \int P(t) \cdot Q(t) \cdot \mathrm{d}t - mP_{aorta}$ is pulsatile power (also called oscillatory power). Pulsatile power is about 15% of total power in the systemic circulation and increases in hypertension. The oscillatory power fraction is about 23% in the pulmonary circulation and the same in health and pulmonary hypertension [3] (see Chap. 28).

16.2 Physiological and Clinical Relevance

It has sometimes been reasoned that it is the mean power that is related to useful power while pulsatile power is related to moving blood forward and reflected only. In other words it was thought that only mean power and work were useful quantities. The logical consequence was then to assume that pulsatile power should be minimal in physiological conditions. This in turn, was used to argue that if the Heart Rate is related to the frequency of the minimum in the input impedance modulus (Chap. 24), pulsatile power would be minimal. However, this is not correct since it is the real part of the impedance that is related to power, not the impedance modulus. Thus, the separation of mean and pulsatile power is not very useful as a measure of ventriculo-arterial coupling. Under physiological conditions the heart pumps at optimal external power (Chap. 18) [4]. Total power is most important.

Work and energy find their main importance in relation to cardiac oxygen consumption, metabolism, and optimal efficiency in ventriculo-arterial coupling.

References

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