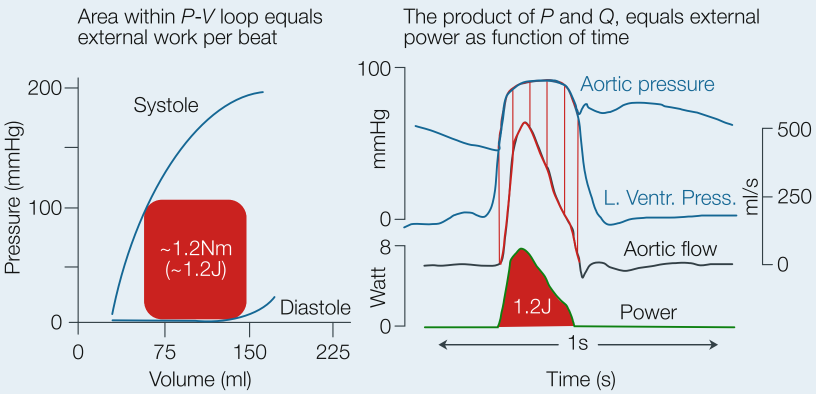
Chapter 15
Cardiac Work, Energy and Power



Ventricular energy production or external work per beat can be determined from the area contained in the pressure-volume loop (*left*). External power (work per unit time) can be calculated from the product of ventricular (or aortic) pressure, *P(t)*, and flow, *Q(t)*, thus *P(t)* ·*Q(t)* in Watt (*right*). The area under the power curve equals energy per beat in Nm or Joules. Mean external power, in Watt equals energy times Heart Rate in beats per second. The calculation of energy and power does not require a linear system, as, for example, the calculation of resistance and impedance. This makes the use of energy and power very broadly applicable in hemodynamics. However, power is a characterization of heart and load together, while the End-Systolic Pressure-Volume Relation and Pump Function Graph characterize the heart and resistance and impedance characterize the arterial system.

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 called power (Nm/s or Watt). Linearity of the relations

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between force and displacement (velocity) or, equivalently between pressure and volume is not required in the calculation of work and power, while it is required in the calculation of resistance and impedance.

In the heart, external work can be derived from pressure and volume through the pressure-volume loop (Chap. 13), 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 stroke work.

Power delivered by the heart to the arterial load equals 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 sufficient 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 two to three times higher than mean left ventricular pressure, using ventricular pressure would lead to considerable errors [1]. The difference between total power and mean power is pulsatile power (also called oscillatory power). Pulsatile power is about 15% of total power (i.e., the oscillatory power fraction is 15%). In systemic hypertension the oscillatory power fraction is increased. In the pulmonary circulation the oscillatory power fraction is about 25%.

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 backward 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 would 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. 23), 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 [2]. See also Chap. 17.

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

Calculations

In hemodynamics the energy per beat equals pressure times volume, and power is calculated from pressure times flow. Energy per beat equals the area within the Pressure-Volume loop (the left part of the Figure in the box). This area equals about 90 ml times 100 mmHg. With 90 ml = $0.09 \cdot 10^{-3}\,m^3$ and 100 mmHg = 13.3 kPa = $13.3 \cdot 10^{+3}$ Pa = $13.3 \cdot 10^{+3}\,N/m^2$. The product of pressure and volume is then $0.09 \cdot 10^{-3}\,m^3 \cdot 13.3 \cdot 10^{+3}\,N/m^2 \approx 1.2$ Nm = 1.2 J. Multiplication by Heart Rate (beats per second) gives, with HR = 60 bpm, an average power output of 1.2 J/s = 1.2 W.

Power as a function of time is the instantaneous product of pressure and flow (right side of the Figure in the box). The area under the power curve is the work per beat, and assuming a triangular shape, the area is about ½ Peak Power times Ejection Time i.e., $\sim \frac{1}{2} \cdot 8 \cdot 0.3 = 1.2$ (Ws = J). Multiplication by HR gives the average power output, also called mean external power.

References

1. Williams SG, Jackson M, Cooke GA, Barker D, Patwala A, Wright DJ, Albuoaini K, Tan L-N. How do different indicators of cardiac pump function impact upon the long-term prognosis of patients with chronic heart failure? *Am Heart J* 2005;150:983.
2. Toorop GP, Van den Horn GJ, Elzinga G, Westerhof N. Matching between feline left ventricle and arterial load: optimal external power or efficiency. *Am J Physiol* 1988;254:H279–H285.