Invasive assessment of cardiac efficiency

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Abstract

The effective energy output divided by the total energy input defines the efficiency of a system. The heart burns substrates and, via several intermediate steps, ultimately produces external work. The efficiency of this process can be measured with invasive techniques that are briefly described in this paper. In addition, we discuss cardiac efficiency in the context of cardiac mechanics and energetics using the pressure–volume framework.
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Introduction

The efficiency of a system is defined as the effective energy output from the system divided by the total energy input into the system. The cardiac pump (or the left ventricle) may be considered as a mechano-chemical transducer that converts chemical energy into heat and external work. The latter is also known as stroke work. In this process, adenosine triphosphate (ATP) is the carrier of chemical energy, which is released during the hydrolysis of ATP into adenosine diphosphate (ADP) and inorganic phosphate (P_i). Because, in the heart, ATP is regenerated almost entirely by oxidative metabolism, cardiac energy consumption can be estimated by measuring oxygen consumption. The metabolic substrates comprise lipids, carbohydrates, and proteins. These substrates have different caloric values (ie, heat liberated per gram of substrate oxidized), and also differ with respect to the amount of oxygen needed to metabolize a gram of substrate. However, when expressed per milliliter of oxygen consumed, their energy equivalents are very similar: approximately 20 J/mL O_2 [1]. Consequently, the total energy input can be estimated by the energy equivalent of myocardial oxygen consumption ($m\dot{V}O_2$), and thus the energy balance of the cardiac pump can be written as:

$$EE \cdot m\dot{V}O_2 = H + EW \qquad (1)$$

where EE is energy equivalents, EW is external work, and H is heat.

If we consider EW as the effective energy output of the heart, cardiac efficiency (CE) is defined as:

$$CE = EW/(EE \cdot m\dot{V}O_2) \qquad (2a)$$

Considering equation (1), alternatives to this expression are:

$$CE = 1 - H/(EE \cdot m\dot{V}O_2) \qquad (2b)$$

$$CE = 1/(1 + [H/EW]) \qquad (2c)$$

Thus, in principle, CE may be obtained by measuring (the ratio of) EW and $m\dot{V}O_2$, H and $m\dot{V}O_2$, or H and EW. In the following, we describe invasive methods of measuring each of these parameters, and briefly discuss cardiac efficiency in the context of cardiac mechanics and energetics.

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Invasive measurement of myocardial oxygen consumption ($m\dot{V}O_2$)

Oxygen consumption by the heart can be determined by the Fick principle as the product of coronary blood flow (CBF) and arterio–venous blood oxygen content difference ($\Delta AVcO_2$) across the coronary bed:

$$m\dot{V}O_2 = CBF \cdot (\Delta AVcO_2) \quad (3)$$

Determination of $\Delta AVcO_2$ requires sampling of blood from the coronary sinus and a systemic artery. Oxygen content is then calculated as the product of hemoglobin concentration (Hb), oxygen saturation (SO_2), and a factor (1.36) representing the oxygen-binding capacity of Hb (free dissolved oxygen can generally be neglected) thus [2,3]:

$$\Delta AVcO_2 = 1.36 \cdot Hb \cdot (SaO_2 - SvO_2) \quad (4)$$

CBF may be determined invasively with reversed thermodilution catheters in the coronary sinus [4,5]. Alternatively, intravascular Doppler techniques (Doppler flow wire) may be used to determine blood flow velocity, which should be combined with an estimate of cross-sectional area of the vessel(s) to calculate CBF [6]. Cross-sectional area may be estimated using quantitative coronary angiography or intravascular ultrasound.

Invasive measurement of cardiac heat (H)

Although heat measurements are used widely to study the energetics of isolated muscle preparations, heat liberated from the heart is difficult to measure in the intact circulation, and only a few attempts have been published [7]. Heat produced by the heart is removed from the myocardium by the coronary circulation (by convection, H_{conv}) or diffused into the mediastinum and the ventricular cavities (H_{diff}). In addition, a small proportion is used in endothermic chemical reactions of oxygen and carbon dioxide with hemoglobin (H_{chem}) [8]. Thus total heat liberated by the heart (H) equals:

$$H = H_{conv} + H_{diff} - H_{chem} \quad (5)$$

H_{chem} was estimated to amount to approximately 1.6 J/mL O_2 consumed, and thus to less than 10% of total heat [9]. H_{conv} may be calculated from the temperature difference between aortic and coronary sinus blood ($\Delta T_{ao\text{-}cs}$), CBF, and the density (ρ_b) and specific heat capacity (C_b) of blood [10]:

$$H_{conv} = CBF \cdot \rho_b \cdot C_b \cdot \Delta T_{ao\text{-}cs} \quad (6)$$

Blood temperatures in the aorta and the coronary sinus can be measured with catheter-mounted thermistors, but, given the very small temperature differences (of the order of 0.2°C), a high accuracy and extremely careful calibration are required. An ingenious method of determining H_{diff} was developed that relies on the assumption that a small amount of heat (or cold) added exogenously to the coronary circulation diffuses in the same way as the endogenous heat produced by myocardial metabolism [9,11]. The ratio of heat recovered in the coronary sinus to the heat introduced into the coronary arteries can be determined experimentally by comparing the areas under the thermodilution curves in the aorta and coronary sinus (A_{ao} and A_{cs}, respectively) after an upstream bolus injection of cold saline. This so-called recovery ratio (R) equals:

$$R = A_{cs}/A_{ao} \quad (7)$$

and, as this also applies to endogenous heat:

$$R = H_{conv}/(H_{conv} + H_{diff}) \quad (8)$$

Thus, combining Eqs. (5), (6), and (8), and neglecting H_{chem}:

$$H = (1/R) \cdot CBF \cdot \rho_b \cdot C_b \cdot \Delta T_{ao\text{-}cs} \quad (9)$$

This approach makes it possible to estimate cardiac heat production with thermodilution techniques in humans [12].

Invasive measurement of external work (EW)

Work is defined as force times displacement, which, for the ventricle, translates into pressure (P) multiplied by volume changes (dV). Thus external work may be calculated by the integral:

$$EW = \int P \, dV \quad (10)$$

In addition to pressure–volume work, the accelerated blood in the aorta represents additional external kinetic work – which, however, is only a small fraction (~5%) and is generally ignored. An elegant way in which to visualize external work is to display the time-dependent pressure and volume signals in a so-called pressure–volume diagram (*Figure 1a*). A cardiac cycle is represented by a counter-clockwise loop and external work is defined by the enclosed area. Strictly speaking, calculation of external work requires the registration of ventricular volume and pressure signals during the cardiac cycle. These signals may be obtained from frame-by-frame analysis of left ventricular contrast angiography combined with pressure measurements using a fluid-filled catheter [13]. More elegantly and more accurately, a conductance catheter may be applied that contains a high-fidelity pressure sensor and several electrodes for conductance measurements to provide simultaneous

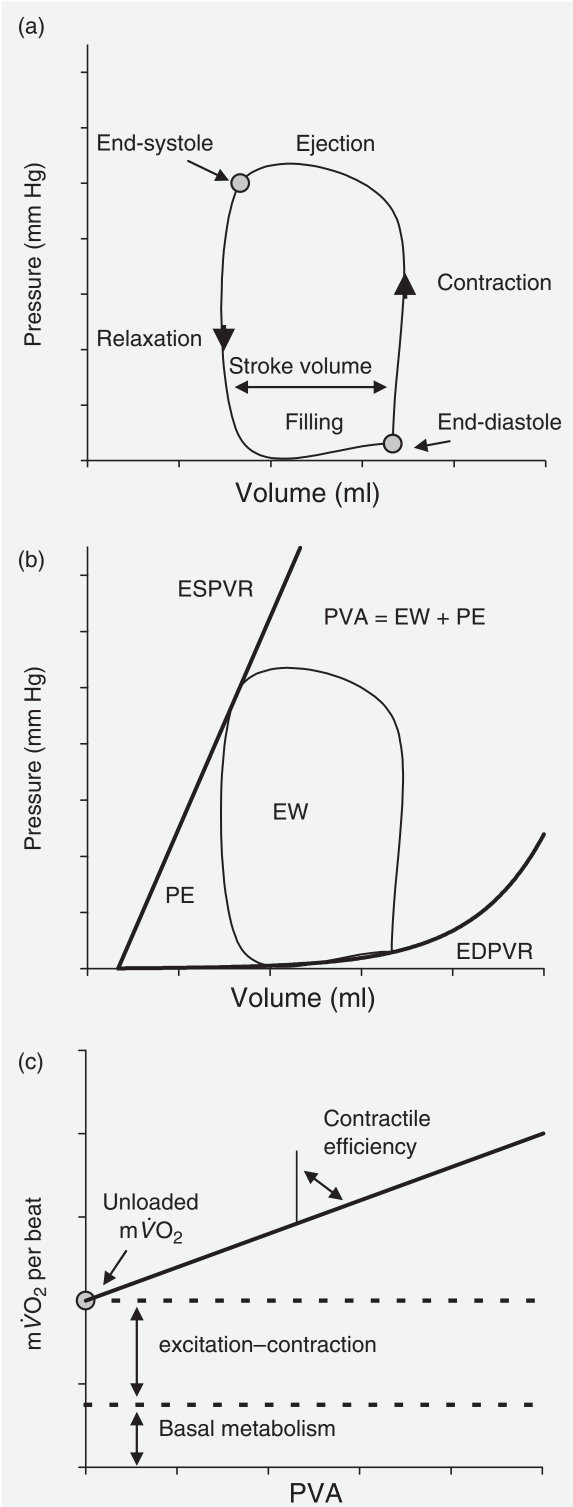

Figure 1. Ventricular mechanics and energetics in the pressure–volume framework. EDPVR, end-diastolic pressure–volume relationship; ESPVR, end-systolic pressure–volume relationship; EW, external work; $\mathrm{m}\dot{V}O_2$, myocardial oxygen consumption; PE, potential energy; PVA, pressure–volume area.

and continuous on-line pressure and volume signals [14,15]. In the absence of valvular insufficiencies and at low diastolic pressures, external work may be approximated by the product of mean ejection

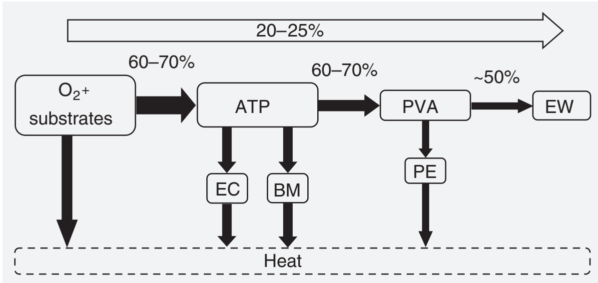

Figure 2. Energy conversions and associated efficiencies (efficiencies indicated as percentages). ATP, adenosine triphosphate; BM, basal metabolism; EC, excitation–contraction; EW, external work; O_2, oxygen; PE, potential energy; PVA, pressure–volume area.

pressure determined in the aorta and stroke volume determined, for example, by thermodilution.

Cardiac efficiency, mechanics, and energetics

The pressure–volume framework provides an excellent tool with which to study and describe the complex relationship between cardiac mechanics, energetics, and efficiencies [16–18]. In this framework, total mechanical energy is represented by the area between the end-systolic pressure–volume relationship, the end-diastolic pressure–volume relationship, and the systolic trajectory of the pressure–volume loop (*Figure 1b*). This so-called pressure–volume area (PVA), consisting of external work and elastic potential energy (PE), was shown to be linearly related to $\mathrm{m}\dot{V}O_2$ (*Figure 1c*). The intercept of the $\mathrm{m}\dot{V}O_2$–PVA relationship, the unloaded $\mathrm{m}\dot{V}O_2$, represents the energy required for activation (excitation–contraction) and basal metabolism. The inverse slope of the $\mathrm{m}\dot{V}O_2$–PVA relationship is referred to as contractile efficiency. This pressure–volume framework illustrates that cardiac efficiency not only depends on intrinsic properties of the heart, but also, strongly, on the loading conditions [19]. In the extreme conditions of isovolumetric contractions (aortic clamping) or unloaded contractions (no pressure development), external work, and thus also cardiac efficiency, is zero. Actual cardiac efficiency is dependent on the ventricular–vascular coupling, and in normal conditions the heart works close to optimal cardiac efficiency [20]. This framework also clarifies the various steps from $\mathrm{m}\dot{V}O_2$ to, ultimately, production of external work. As illustrated in *Figure 2*, at each level part of the energy is dissipated into heat and thus each step codetermines the overall cardiac efficiency. Because disease conditions, in general, affect efficiencies at specific levels, and because interventions are generally targeted to optimize energy conversions at a specific level, these intermediate steps are important to consider when interpreting measurements of cardiac efficiency. ■

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