Editorial

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Myocardial Efficiency: A Reliable Load-independent Parameter of Cardiac Performance?

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As an mechanical engine, the efficiency of heart can be summarized as the ratio of external work (EW) and the oxygen uptake of myocardium in a given time, which was initially suggested by Bing et al in 1949.[1)2)] The definition of myocardial efficiency (MEf), in usual clinical and research settings, include only left ventricle (LV), while the work and metabolism of right ventricle and atria are neglected. Also, the MEf accounts the EW of LV, but not the potential energy of LV which indicates the work required to expand the LV to its actual minimal volume (LV end-systolic volume). Under these assumptions, the MEf is calculated using the product of EW of LV and heart rate, divided by the product of myocardial oxygen consumption (mVO_2) and LV mass (LVM) (**Figure 1**). The EW, or stroke work (SW) indicates the area contained in a pressure-volume loop of LV (**Figure 1**), and can be approximately estimated as a product of stroke volume (SV) and end-systolic pressure, or a product of SV and mean arterial pressure (MAP).

The mVO_2 can be measured with invasive cardiac catheterization, or with the use of radioactive isotope; inhaled ^{15}O-labeled oxygen gas, or generally, injected ^{11}C-acetate. After intravenous injection, the ^{11}C-acetate is transformed to ^{11}C-acetyl-CoA in myocardium and enters the tricarboxylic acid cycle where it is metabolized to ^{11}C-CO_2.[1)] The myocardial time-activity curve shows a biexponential clearance (rapid phase [k_1] and slow phase [k_2]), and the rate of ^{11}C-CO_2 clearance is monoexponential under steady hemodynamic conditions and is linearly related to oxygen uptake, which indicates the myocardial oxidative metabolism (**Figure 1**). Thus, the clearance rate of ^{11}C-activity (k_2) is used for the calculation of mVO_2, which is in the denominator of the MEf equation. As a simplified method, Beanlands et al.[3)] introduced an alternative measure of efficiency index, the work-metabolic index (WMI), using the monoexponential time constant (k_{mono}) of the linear part of time-activity curve (**Figure 1**). The measurement of SV, as well as LVM, is performed by non-invasive tests including echocardiography, magnetic resonance, computed tomography, or positron emission tomography (PET).[4-6)]

Previous studies showed that the MEf is decreased in patients with hypertension, heart failure (HF), aortic stenosis (AS), and mitral regurgitation (MR).[6-13)] Furthermore, therapeutic intervention to these volume and/or pressure-overloaded conditions alleviate the MEf

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A

Potential energy (PE) = Internal cardiac work
$\qquad$ = the work required to expand the ventricle
$\qquad$ to its actual minimal volume

External work (EW) = Stroke work (SW)
$\qquad$ = Area contained in the PV loop
$\qquad$ $\cong$ Stroke volume (SV) $\times$ LV end-systolic pressure
$\qquad$ $\cong$ SV $\times$ mean arterial pressure (MAP)

B

k_1 (rapid phase) = efflux of $^{11}CO_2$ produced by the TCA cycle
k_2 (slow phase) = clearance of ^{11}C-activity (washout rate)
k_{mono} = simplified monoexponential curve fit of the linear part

$$\text{Work-metabolic index (WMI)} = \frac{\text{SBP} \times \text{SVi} \times \text{HR}}{k_{mono}}$$

$$\text{Myocardial efficiency (MEf)} = \frac{\text{EW} \times \text{HR}}{\text{mVO}_2 \times \text{LVM}}$$

$$= \frac{\text{MAP (mmHg)} \times \text{SV (mL/beat)} \times \text{HR (beats/min)} \times 1.33 \times 10^{-4}}{\text{mVO}_2 \text{ (mL/g/min)} \times \text{LVM (g)} \times 20}$$
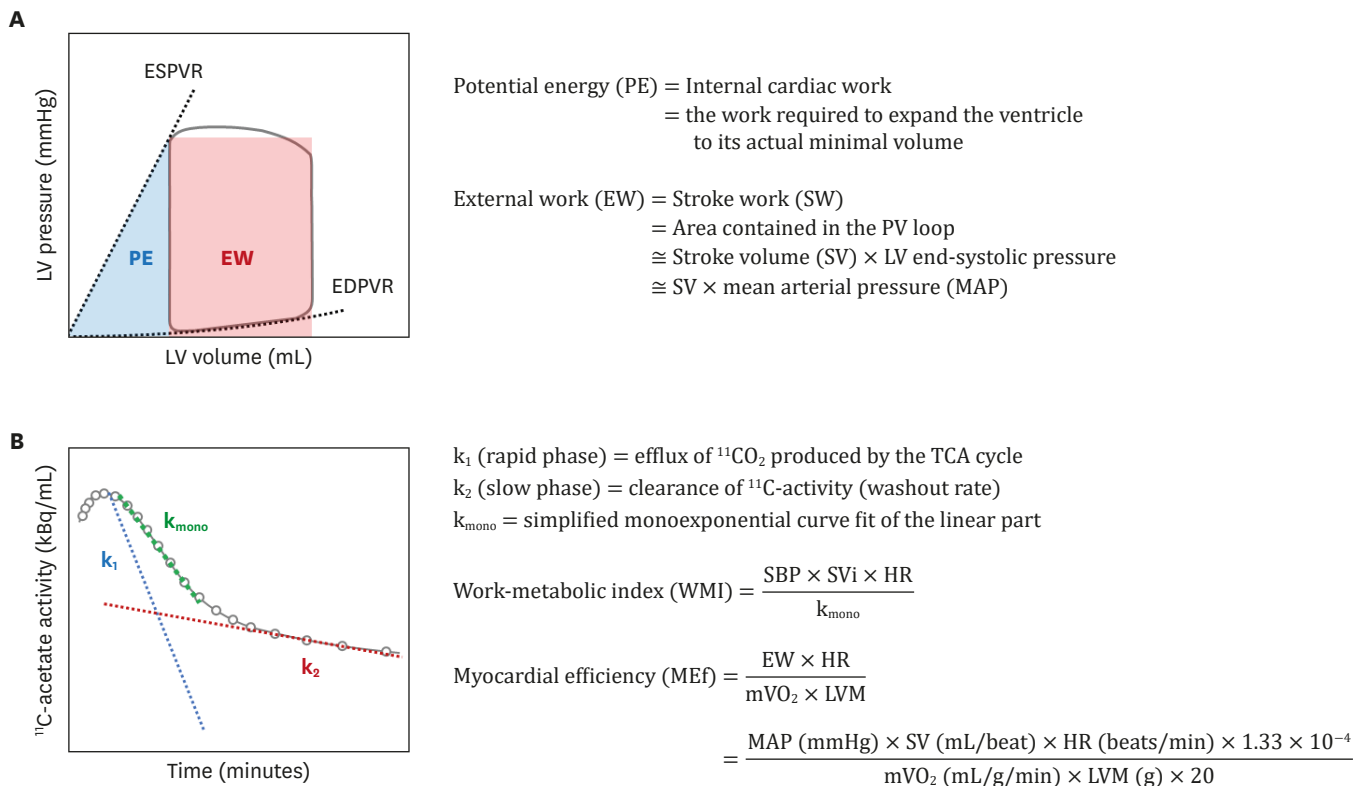
Figure 1. Non-invasive measurement of myocardial efficiency. (A) In the non-invasive calculation of MEf, the EW which indicates the area contained in the PV loop is approximated as a product of SV and MAP. (B) The time constants (k_1, k_2, and k_{mono}) are obtained from the myocardial time-activity curve of ^{11}C-acetate PET. The WMI is calculated using the simplified k_{mono} of decay for ^{11}C-acetate, and the mVO_2 (which is in the denominator of MEf equation) is calculated from the washout rate of ^{11}C-activity (k_2).
MEf: myocardial efficiency; EW: external work; PV: pressure-volume; SV: stroke volume; MAP: mean arterial pressure; k_1: rapid phase; k_2: slow phase; k_{mono}: monoexponential time constant; PET: positron emission tomography; WMI: work-metabolic index; mVO_2: myocardial oxygen consumption; LV: left ventricular; PE: potential energy; ESPVR: end-systolic pressure-volume relationship; EDPVR: end-diastolic pressure-volume relationship; TCA: tricarboxylic acid; SBP: systolic blood pressure; SVi: stroke volume index; HR: heart rate; LVM: left ventricular mass.

through decreased mVO_2, reduced LVM, and increased EW. For example, the afterload reduction by aortic valve replacement improved MEf through LV reverse remodeling and reduced mVO_2, in conjunction with an increase in EW, in patients with severe AS.[9] The improvement of WMI was also observed in patients with severe MR at 1-year after MV replacement.[11] These studies support the potential usefulness and feasibility of MEf in various cardiac diseases.

In this paper of *Journal of Cardiovascular Imaging*, the authors compared the MEf in patients with severe MR and healthy volunteers, using parameters obtained from echocardiography.[14] Although the LV-ejection fraction (EF) and forward SV were preserved in patients with MR, the mVO_2 was significantly increased, and thus, the MEf was markedly reduced. Adding to the main finding on the reduced MEf in patients with severe MR, the authors further reported that the patients with severe MR who were on both beta-blockers and renin-angiotensin system (RAS) blockers tended to have a higher MEf, compared to the patients without these medications. This finding corresponds to the established benefits of these cardioprotective medications: beta-blockers reduce mVO_2, and RAS blockers reduce afterload and augment forward SV. Also, it is in concordance with previous studies that reported the improved MEf by the use of beta-blockers in patients with HF, which was accompanied with improved LV-EF and increased SW, and reduced oxygen consumption.[15][16]

Theoretically, the concept of MEf is convincing as it considers the actual EW corrected to the consumption of oxygen, and also includes the loading condition (product of SV and MAP). Adding to this, the MEf has further strengths over traditional parameters: MEf reveals the metabolic status of myocardium, which may enable a more sensitive detection of benefits of medical therapy in a diseased myocardium. Indeed, traditional parameters are largely based on the motion of myocardium, which should be the final stage output from the impaired myocardial energetics and disturbed loading conditions. Furthermore, the increasing number of facilities equipped with cyclotron is a factor that causes the utilization of MEf to increase in the future.

Despite these potential strengths of MEf, there are several issues to be further investigated for its wider clinical application. First, the reference rage of MEf significantly varies according to the methods of measurement. The standardization and validation between modalities (echocardiography, magnetic resonance, computed tomography, and PET) are required. Second, the equation of MEf calculation is based on several assumptions and approximations. This is not limited to the innate assumptions of the imaging modalities, but also to the assumptions for the SW of the heart. Third, supporting evidence for the assessment of MEf and its changes according to therapeutic interventions is still limited to a few disease groups.

At present, it can be suggested that the MEf has a potential as a useful non-invasive, load-independent tool for assessment of LV performance, and for the monitoring of treatment response. Future studies investigating the role of MEf in various disease population are warranted. Also, it is important to understand the characteristics of MEf and related parameters, how to measure them, and the remaining limitations.

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