letters to the editor

Optimal external power or efficiency?

To the Editor: In a recent study, Toorop et al. (3) set out to determine whether arterial and left ventricular properties are matched such that either ventricular stroke work or ventricular efficiency (stroke work/oxygen consumption) is maximized. Experiments were performed on anesthetized, open-chest cats. The authors conclude that for this preparation, arterial and ventricular properties are adjusted so as to maximize stroke work. They state that this experimental finding contradicts the theoretical prediction we made previously (1) that under physiological conditions ventricular efficiency would be maximized.

In our assessment, no contradiction exists. In the presence of anesthesia and surgical thoracotomy, cardiovascular system properties are altered extensively: heart rate increases, ventricular contractility decreases, and systemic arterial resistance increases. As indicated in our analysis (1), each of these changes pushes the work point of the system away from maximal efficiency toward maximal stroke work. We believe that these are the circumstances under which Toorop and his colleagues examined the ventriculoarterial matching and found the maximal stroke work condition.

In our theoretical analysis (2), we inferred that the natural matching in intact animals and humans may be such that efficiency is maximized. This conclusion was an inference, not an experimental finding in the isolated ventricle. Toorop might have overlooked this when he wrote "the analytical findings of Burkhoff and Sagawa (2) based on the isolated heart ... " (see the summary statements in their DISCUSSION). This is not true at all. We estimated physiological values for the end-systolic elastance of the left ventricle (E_{es}) and arterial effective elastance afterload (E_a) from the values of stroke volume, heart rate, and total peripheral resistance reported by other investigators in intact, resting dogs. If we substitute the parameter values that we measure in anesthetized open-chest dogs, then our model predicts, in concordance with the study of Toorop et al., that stroke work is maximized.

Toorop and co-authors interpreted previous experimental findings from Sunagawa et al. (2) as showing that the isolated heart pumps at the point of maximal stroke work. This is also an incorrect interpretation of the data presented in that paper. The data of Sunagawa et al. (2) merely show that at any level of contractility and heart rate there exists an arterial resistance at which stroke work is maximized. This is entirely different from the interpretation by Toorop et al. that the isolated heart pumps at maximal efficiency. Since heart rate, contractility, and simulated arterial resistance in the isolated heart can be set arbitrarily at whatever values the investigator chooses, it is inappropriate and impossible to discuss the existence of a naturally occurring working point based on data from the isolated heart in a manner analogous to the way we can in the intact animal.

Finally, the authors indicated that the efficiency predicted by our model at the proposed working point was only 13.5% and far from the value of 20% measured experimentally. In fact, when one goes through the calculations, our model predicts an efficiency of 18%, which is close to the experimental value.

In summary, we submit that there is no contradiction between our model predictions and the experimental results of Toorop et al. (3) and that they have compared apples and oranges. Furthermore, we contend that our prediction of optimized efficiency under physiological conditions remains viable. Resolution of the issue can come only from data from the physiologically intact, unperturbed animals and humans.

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REPLY

To the Editor: When external power output (pressure times flow and proportional to stroke work for constant heart rate) and efficiency (the ratio of external power output and input power or oxygen consumption per time) are determined for different loads, the power maximum is found at smaller flow values or larger load values than maximum efficiency (4). The question underlying the present debate is whether the intact heart normally works at maximum power output or at maximum efficiency.

In the anesthetized open-thorax cat, we found that power output is maximal, rather than efficiency (9). As discussed in our paper (9), the experimental conditions may have influenced the properties of heart and arterial tree and, as a consequence, the results may not apply directly to the conscious animal. However, our result seems consistent with findings in the conscious dog (11). Sunagawa et al. (8) concluded from data obtained in the isolated dog heart preparation, that "maximal external work may be the optimization criterion in intact animals as well."

On the other hand, Burkhoff and Sagawa (2) concluded on basis of a mathematical model, originally proposed by Sunagawa et al. (8), that in the conscious dog under normal physiological conditions the heart works at maximal efficiency. In our paper we questioned this conclusion. The theoretical approach presented by Burkhoff and Sagawa (2) is attractive because of its simplicity (i.e., superfluous properties were carefully omitted and because various relationships can be simulated with the model. Nevertheless, the choice of parameter values remains arbitrary because the reported physiological ranges are rather broad. The data reported by Little et al. (Fig. 2 in Ref. 5, for example) indicate that the end-systolic elastance is 7 mmHg/ml. For the same example, stroke volume without vena caval occlusion (i.e., the working point) is 15 ml, corresponding to an end-systolic pressure of 105 mmHg and resulting in an arterial elastance (end-systolic pressure over stroke volume) of 7 mmHg/ml. Thus end-systolic ventricular elastance may be the same as arterial elastance in the closed-chest dog, which suggests that the heart pumps at maximal power output (8). Moreover there are indications that the end-systolic pressure-volume relation may not be linear (3, 6) and may not be load independent (1) as assumed in the model (2). Also, several simplifications assumed in the derivation of the model may be of influence. Examples are the linear relation between the pressure-volume area and oxygen consumption, the inclusion of the area under the diastolic pressure-volume relation in the pressure-volume area, the approximation of the arterial tree with the three-element Windkessel model (10), and the choice that end-systolic pressure equals mean arterial pressure.

Burkhoff and Sagawa (2) listed the following physiological ranges of model parameters: E_{es} = 4–9 mmHg/ml; E_a = 4–7 mmHg/ml, V_0 = 5–10 ml, and V_{ed} = 25–40 ml. Using the medians of these values results in an efficiency of 11% on the basis of the models of Burkhoff and Sagawa (2) and Suga et al. (7). Inserting the values of the parameters actually used by Burkhoff and Sagawa, some of which are out of the above ranges, E_a = 3.3 mmHg/ml and V_{ed} = 45 ml, results in an efficiency of 18.5 and 13.5% for these two models. Thus there exists a discrepancy in the model predictions and a lack of accurate information on the parameters so that a firm conclusion cannot as yet be drawn.

We conclude that Burkhoff and Sagawa's model may be a useful tool in the analysis and interpretation of experimental data. Given the simplifying assumptions in the model and the uncertainty of the data of the conscious dog, detailed quantitative predictions remain speculative.

Experiments similar to ours, but performed on the conscious animal, are necessary to be able to decide whether or not the heart in the concious animal works at maximal power.

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