Circulation: Heart Failure

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Effective Arterial Elastance in the Pulmonary Arterial Circulation

Derivation, Assumptions, and Clinical Applications

Michael I. Brener, MD; Daniel Burkhoff, MD, PhD; Kenji Sunagawa, MD, PhD

Current understanding of ventricular-vascular interactions is largely based on the seminal works of (1) Guyton,[1] who developed and validated the first comprehensive models of the circulatory system; (2) Suga and Sagawa,[2] who introduced the time-varying elastance model and E_{es}, the slope of the end-systolic pressure-volume relationship, to characterize ventricular properties; and (3) Sunagawa et al,[3] who created the concept of effective arterial elastance (E_a) to depict vascular properties on the ventricular pressure-volume diagram. These efforts advanced understanding of ventricular-vascular coupling and led to the observation that maximal transfer of mechanical stroke work from the left ventricle to the systemic arterial circulation occurs when $E_a \approx E_{es}$.[4] Furthermore, important aspects of the hemodynamic abnormalities of acute and chronic heart failure and hypertension occur when the E_a/E_{es} ratio deviates from normal—a condition commonly referred to as ventricular-vascular uncoupling or mismatch.

Recently, increased attention to ventricular-vascular interactions between the right ventricle (RV) and pulmonary arterial (PA) circulation has led to observations that abnormal effective PA elastance ($E_{a,PA}$) is associated with adverse clinical outcomes.[5] Most such contemporary studies apply the same framework originally used to derive E_a in the systemic circulation for estimating $E_{a,PA}$. However, the fundamental assumptions required to simplify the equations used to estimate E_a in the systemic circulation are not valid for the pulmonary circulation, warranting further discussion.

DERIVATION OF E_a IN THE SYSTEMIC ARTERIAL CIRCULATION

The derivation of E_a for the systemic circulation starts with the formula for total peripheral resistance (TPR), which integrates measurements of mean arterial pressure (MAP), central venous pressure (CVP), and cardiac output (CO). After decomposing CO into the product of stroke volume (SV) and heart rate (HR), we see that

$$TPR = \frac{MAP - CVP}{CO} = \frac{MAP - CVP}{SV \times HR} \quad (1)$$

Two critical assumptions are then made to simplify this equation: (1) that central venous pressure is negligible compared with mean arterial pressure under normal physiological conditions and (2) that mean arterial pressure can be approximated by ventricular end-systolic pressure (P_{es}). Incorporating these assumptions and rearranging the terms leads to

$$TPR \times HR \approx \pi \frac{P_{es}}{SV} \equiv E_a \quad (2)$$

Although E_a has multiple advantages as an index of arterial load, we note that it does not fully characterize pulsatile load; analyses of time-varying pressure-flow relations that characterize the impact of wave reflections represent powerful complementary approaches to assess ventricular-arterial coupling.[6] A third simplifying assumption relates to estimation of stroke volume, which is the difference between end-diastolic volume (V_{ed}) and the volume at end ejection (V_{ee}). To facilitate graphical depiction of E_a on the left ventricle pressure-volume diagram,

Key Words: heart ventricles ■ hemodynamics ■ pulmonary artery ■ vascular stiffness

Correspondence to: Michael I. Brener, MD, Division of Cardiology, Department of Medicine, Columbia University Medical Center, 630 W 168th St, Box 93, New York, NY 10032. Email mib2102@cumc.columbia.edu

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it is assumed that V_{ee} is equivalent to the volume at end systole (V_{es}), which is the point on the pressure-volume loop that intersects with the end-systolic pressure-volume relationship.

These 3 assumptions have formed the basis for the prevailing depiction of E_a on the left ventricle pressure-volume diagram over the last 35 years, culminating in E_a being represented by the slope of the line connecting the point on the volume axis corresponding to end-diastolic volume (V_{ed}, 0) with the point on the pressure-volume loop at end systole (V_{es}, P_{es}; Figure [A], dotted line).[3] If, on the other hand, these assumptions are not accepted, the E_a line would originate at point (V_{ed}, CVP) and go through the point (V_{ee}, MAP), as depicted by the solid line. There is no significant difference, as you can appreciate, between these 2 lines or their slopes.

REPRESENTING $E_{a,PA}$ ON THE RV PRESSURE-VOLUME DIAGRAM

The most commonly used formula to quantify $E_{a,PA}$ in the literature is

$$E_{a,PA} = \frac{PASP}{SV} \quad (3)$$

where PAS is pulmonary artery systolic pressure. The value of $E_{a,PA}$ is depicted graphically and then by the slope of the line originating at point (V_{ed}, 0) and connecting to the point (V_{ee}, PASP), as shown by the dotted line in Figure (B).

If we begin deriving $E_{a,PA}$ as we did for E_a for the systemic circulation with the formula for pulmonary vascular resistance (PVR), the correlate of TPR in the pulmonary circulation, we arrive at the following relationship

$$PVR \times HR = \frac{PAP_{mean} - PCWP}{SV} \equiv E_{a,PA} \quad (4)$$

where PAP_{mean} is the mean PA pressure and PCWP is pulmonary capillary wedge pressure. Equation 4 can be restated if stroke volume is expressed as the difference between V_{ed} and V_{ee}:

$$E_{a,PA} \equiv \frac{PAP_{mean} - PCWP}{V_{ed} - V_{ee}} \quad (5)$$

However, the assumptions that helped reduce Equation 1 into Equation 2 for estimation of E_a in the systemic circulation cannot be applied to simplify Equation 5 into Equation 3 for estimation of $E_{a,PA}$. First, PCWP is not negligible relative to PAP_{mean}, even under normal conditions, and thus, the origin of the theoretically more sound $E_{a,PA}$ line is determined by the point (V_{ed}, PCWP). Second, it is the nature of RV-PA interactions that ejection continues past the point of end systole, which is the point on the pressure-volume loop that intersects with the end-systolic pressure-volume relationship; accordingly, V_{ee} and P_{ee} are both smaller than V_{es} and P_{es}, respectively. Therefore, the slope of the line depicting $E_{a,PA}$ differs if the line passes through coordinates (V_{ee}, PASP), as discussed above and shown by the dotted line in Figure (B), the end-systolic point (V_{es}, P_{es}), as used for the determination

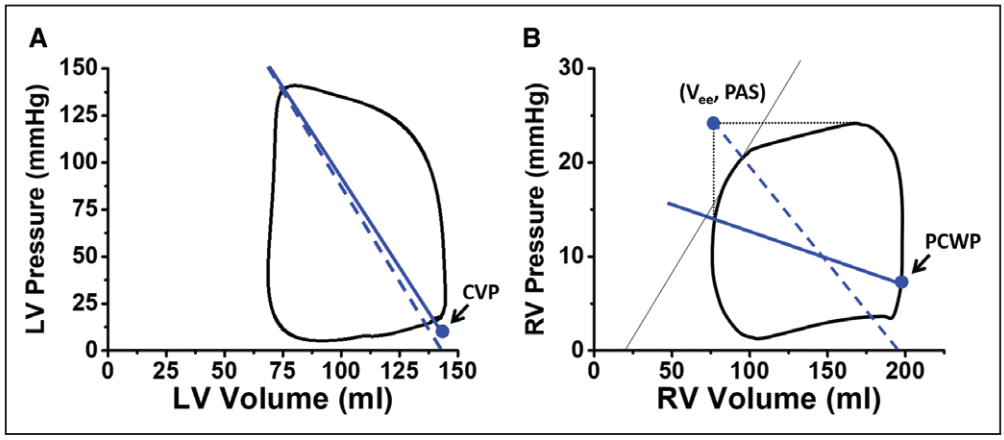

Figure. Ventricular pressure-volume diagrams illustrating the effect of routinely used simplifications to the formula for effective arterial elastance in the systemic and pulmonary arterial circulation.

A depicts a typical left ventricular (LV) pressure-volume loop in a patient undergoing left heart catheterization (courtesy of Michael Brener, Amirali Masoumi, Dimitri Karmpaliotis, and Daniel Burkhoff). The slope of the dotted line represents arterial elastance in the systemic circulation estimated using a formula (Equation 2) that is simplified through a number of assumptions discussed in the text from the original equation, which is represented by the solid line. Given the similarities in the slopes of each line, E_a for the systemic circulation can be appropriately estimated using the following equation: $E_a = P_{es}/(V_{ed} - V_{es})$. **B** illustrates a right ventricular (RV) pressure volume loop in a healthy subject undergoing exercise physiology testing. †In contrast to **A**, the dotted line, derived from the formula used for estimating Ea in the systemic circulation, differs substantially from the solid line, which is calculated with the following formula: $E_{a,PA} = (PAP_{mean} - PCWP)/(V_{ed} - V_{ee})$. Panel **B** is adapted from Cornwell et al[7] with permission. Copyright © Wolters Kluwer 2018. CVP indicates central venous pressure; E_a, effective arterial elastance; $E_{a,PA}$, effective pulmonary arterial elastance; PAP_{mean}, mean pulmonary arterial pressure; PAS, pulmonary artery systolic pressure; PCWP, pulmonary capillary wedge pressure; P_{es}, end-systolic pressure; V_{ed}, end-diastolic volume; V_{ee}, volume at end ejection; and V_{es}, end-systolic volume.

of E_a, or, as indicated by Equation 5, through (V_{ee}, PAP_{mean}) and depicted by the solid line in Figure (B).

In summary, the proposed formula for $E_{a,PA}$ and the accompanying discussion emphasizes 3 key points: (1) PCWP contributes importantly to RV afterload independent of pulmonary vascular properties; (2) $E_{a,PA}$, as described by Equations 4 and 5, relates to PVR and HR and is independent of PCWP, making it directly analogous to the concept represented by E_a in the systemic circulation; and (3) the relative contributions of PCWP and PVR to abnormalities of RV-PA coupling are more readily quantified with this approach.

We believe the proposed formula for $E_{a,PA}$ more closely aligns with the original, intended purpose of the concept of effective E_a, which was to provide a simple analytical framework for understanding ventricular-vascular interactions.[3] The proposed formula does not diminish prior findings showing that PAS/SV (the previously used definition of $E_{a,PA}$) correlates with clinical outcomes.[5] Rather, it provides additive insights and allows us to understand the role of constituent parameters of RV afterload (ie, PVR, HR, and PCWP) so that disease mechanisms can be clarified and specific therapeutic targets can be identified.

ARTICLE INFORMATION

Affiliations

Division of Cardiology, Department of Medicine, Columbia University Medical Center, New York (M.I.B.). Cardiovascular Research Foundation, New York (D.B.). Center for Disruptive Cardiovascular Medicine, Kyushu University, Fukuoka, Japan (K.S.).

Disclosures

None.

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