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Opinion

Modeling Cardiac Response to Transient Hemodynamic Changes: Beyond dp/dt Max and New Insights from IVCO and ES Point Analysis

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Received: 24 September 2025; Accepted: 26 September 2025; Available online: 29 September 2025

ABSTRACT: Traditional indices such as dp/dt max remain widely used in assessing ventricular contractility, yet their load-dependence limits clinical precision, particularly during dynamic hemodynamic shifts. This *letter to the Editor* advocates for a more physiologically grounded approach using dual pressure catheters equipped with two high-fidelity sensors, one in the left ventricle (LV) and one in the aorta, to capture real-time pressure gradients and valve events with high temporal resolution. When combined with transient inferior vena cava occlusion (IVCO), this setup enables accurate identification of the true end-systolic (ES) point, typically marked by dp/dt min or the dicrotic notch on the aortic pressure waveform. This method allows for the construction of more physiologically valid end-systolic pressure-volume relationships (ESPVR). It introduces the novel peak pressure end-systolic pressure-volume relationship (PPESPVR) model, which links peak LV pressure to the ES point within a single cardiac cycle. The resulting volume intercept (Vint) and end-systolic fraction (ESF) offer new insights into myocardial performance under varying preload and afterload conditions, without requiring extensive hemodynamic manipulation. This dual-sensor approach not only enhances diagnostic accuracy but also opens the door to real-time, patient-specific contractility assessment in both research and clinical settings.

Keywords: Cardiac contractility assessment; Pressure-volume loop (PVL) modeling; End-systolic elastance (Ees); ESPVR (end-systolic pressure-volume relationship); PPESPVR (peak pressure end-systolic pressure-volume relationship)

1. Hemodynamic Framework for Assessing Inotropy

Cardiac performance is commonly framed in terms of load-dependent and load-independent measures of contractility. The load-dependent approach reflects the Otto-Frank-Starling mechanism, where changes in preload and afterload shift the relationship between stroke volume and LVEDP. Static indices such as ejection fraction, LV dp/dt max, maximal aortic flow acceleration, or global longitudinal strain provide useful but geometry and load-sensitive markers of inotropy. The Ejection Fraction (EF), for instance, is strongly influenced by ventricular shape and afterload (Ea), while dp/dt max, though relatively afterload-insensitive, remains preload-dependent, hence corrections such as dp/dt max/EDV [1]. Wall stress, derived from Laplace's law, offers only a broad view of afterload given LV heterogeneity. To overcome these limitations, load-independent assessment is achieved by transiently altering preload or afterload while holding the other constant, often via vena cava or aortic occlusion. These maneuvers allow the derivation of end-systolic elastance (Ees) and its intercept, which is a more robust index of intrinsic contractility, though still influenced by heart rate and loading conditions. Both load-dependent and load-independent models provide complementary clinical insights into the hemodynamic expression of inotropy [2].

2. The Limitations of dp/dt Max

While dp/dt max offers a quick snapshot of contractile force, it is inherently load-dependent, influenced by both preload and afterload conditions [3]. In clinical and experimental settings where these variables fluctuate, sometimes

https://doi.org/10.70322/cvs.2025.10009

rapidly, dp/dt max can misrepresent true myocardial performance. This limitation becomes especially pronounced in scenarios involving acute volume shifts, pharmacologic interventions, or during mechanical circulatory support.

3. Entrance to Load-Independent Insights by Transiently Limit Cardiac Preload

Inferior vena cava occlusion (IVCO) has emerged as a powerful technique to transiently reduce preload in invasively catheterized patients, allowing for the generation of pressure-volume loops under controlled conditions [4]. By observing the heart's response to these brief loading changes, clinicians and researchers can derive load-independent indices such as end-systolic elastance (Ees) and volume intercept (V_0), metrics that more accurately reflect intrinsic myocardial contractility. However, the true potential of IVCO lies not just in its ability to isolate contractile function but in its capacity to reveal nuanced physiological transitions within the cardiac cycle. When paired with high-fidelity pressure and volume data, IVCO enables the identification of true end-systolic (ES) points, which often differ from the traditionally used maximal PV corner points.

A dual pressure catheter is a specialized medical device that simultaneously measures left ventricular pressure (LVP) and aortic pressure (AoP) in real time.The catheter has two pressure sensors that could be positioned in the left ventricle to record LVP, another in the ascending aorta to record AoP. This dual-channel setup allows for precise detection of pressure gradients, valve events, and timing of systolic phases, which are critical for identifying true end-systolic points and contractile performance [5]. With high temporal resolution, the catheter captures dp/dt max, the peak rate of pressure rise in the LV, which is traditionally used as a contractility index. dp/dt min: the peak rate of pressure fall, often used to identify aortic valve closure (end-systole). Dicrotic notch on AoP: confirms valve closure and aligns with dp/dt min. These markers help define the ejection phase and end-systolic point (ES) more accurately than volume-based estimates alone.

4. The ES Points Serve as a Physiological Anchor

Recent modeling efforts have shown that the ES point, defined by markers such as dp/dt min or the dicrotic notch on the aortic pressure trace, provides a more physiologically accurate representation of the end of systole [5]. Unlike the automated corner detection methods, which may misalign with actual valve closure, the ES point reflects the mechanical and electrical culmination of systole, offering a more reliable anchor for assessing contractility [5]. This distinction is not trivial. When constructing ESPVR curves, using ES points instead of max PV points yields different slopes and intercepts, potentially altering clinical interpretations and therapeutic decisions. Moreover, the introduction of PPESPVR, a novel relationship connecting peak pressure (PP) and ES volume, offers a fresh lens through which to view systolic function, even under load-dependent conditions. The implications of these insights are profound. By integrating IVCO, ES point analysis, and PPESPVR modeling, we move closer to a multi-dimensional understanding of cardiac mechanics that respects the interplay between geometry, timing, and pressure-volume dynamics. This approach not only enhances diagnostic accuracy but also opens doors to personalized hemodynamic profiling, especially in complex cases like heart failure, valvular disease, or post-operative recovery.

This work matters because dual pressure catheter data move beyond traditional single-point metrics like dP/dt max by providing a cycle-specific assessment of contractility, enabling detection of subtle yet clinically relevant changes in systolic function during interventions such as inferior vena cava occlusion. Dual-pressure measurements in swine models under altered inotropy demonstrate relatively stable transfer of pressure waves to the ascending aorta. Aortic valve timing, central to late systolic ejection, is closely linked to LV pressure decay and stroke work, which declines with reduced stroke volume under constant afterload. Pressure-volume analysis further highlights the linear relationship between stroke work and preload [5]. By capturing the true mechanical end of systole with greater precision, this approach enhances the accuracy and reliability of functional assessment, offering a more nuanced understanding of cardiac performance that could ultimately inform both experimental physiology and translational applications in heart failure management, e.g., HFpEF, HFrEF.

Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data will be available upon request.

Funding

This research received no external funding.

Declaration of Competing Interest

The author declare that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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