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Invited Editorial

Continuous blood pressure-derived cardiac output monitoring—should we be thinking long term?

Cardiac output, along with cardiac filling pressure, arterial blood pressure, and heart rate, is one of the most important hemodynamic variables to monitor continuously in patients with compromised cardiovascular performance. This point is illustrated strikingly in Fig. 1, which shows an example of severe, acute hemorrhage (1). During blood loss, the commonly monitored systolic arterial blood pressure fell by a nonspecific amount, whereas cardiac output and right atrial pressure dropped precipitously (by 30–40%), providing clear warning of the impending hemodynamic crisis. Similarly, cardiac output and cardiac filling pressure measurements are invaluable for the early diagnosis, monitoring of disease progression, and titration of therapy in heart failure, shock of any type, sepsis, and during cardiac surgery to mention just a few conditions.

Current clinical standards for determining cardiac filling pressure and cardiac output unfortunately require highly invasive catheterization of the right heart and are therefore restricted to a small fraction of the sickest of patients, commonly a subset of those in intensive care. Even in those circumstances in which a pulmonary artery catheter is in place, measurements of left ventricular filling pressure and cardiac output are commonly performed only intermittently, as they require the proper placement and inflation of the balloon-tipped catheter or the administration of cold saline into the pulmonary artery. Finally, the benefit of the pulmonary artery catheter has been called into question repeatedly (6), which might ultimately lead to a reduction in its use and consequently a reduction in the number of cardiac output measurements performed.

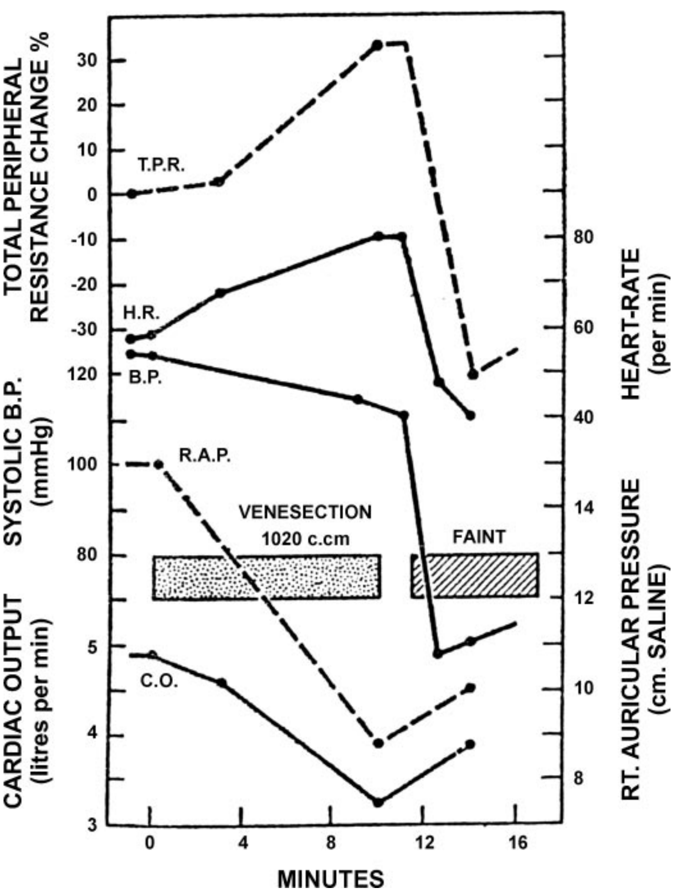

Fig. 1. Example of severe, acute hemorrhage. [Reprinted from (1), with permission from Elsevier.] TPR, total peripheral resistance; HR, heart rate; BP, blood pressure; RAP, right atrial pressure; CO, cardiac output; RT, right.

There is evidently a pressing need for automated (i.e., operator independent), continuous (rather than sporadic), and ideally non- to minimally invasive monitoring of absolute or even relative changes in cardiac filling pressure and cardiac output, especially when faced with an aging population. In this issue of the *Journal of Applied Physiology*, Lu and Mukkamala (4) take on the latter challenge, namely that of estimating relative changes in cardiac output from non- to minimally invasive peripheral arterial blood pressure recordings.

Since Otto Frank's (2) quantitative analysis of the arterial pressure pulse appeared over 100 years ago, researchers have devised several methods to estimate cardiac output on a beat-by-beat basis from features of the central aortic or the peripheral arterial pressure waveform. These methods have in common that each individual arterial pressure wavelet is analyzed mathematically, so as to extract an estimate of stroke volume on a beat-by-beat basis. Lu and Mukkamala argue, however, that over these short time scales, the contribution of wave reflection phenomena to the arterial pressure pulse significantly impairs the derivation of reliable stroke volume estimates from the arterial pressure pulse contour. Rather than analyzing the short time scale (intrabeat, high frequency) variation in arterial blood pressure wavelets, they recognize and exploit the fact that the average flow in the arterial tree may be modeled as a windkessel in the limit of long time scales (interbeat or low-frequency variations). This realization by itself is not new. However, the authors draw the insightful conclusion that the exponential diastolic decay in arterial blood pressure predicted by the windkessel theory should best be observable over time scales long enough for typical high-frequency phenomena (such as wave reflections) to subside. The approach taken is quite innovative and different from previous methods of estimating the windkessel time constant directly from the diastolic portion of individual arterial pressure wavelets. Instead, Lu and Mukkamala rely on the analysis of arterial blood pressure variability over a window that is long (6 min in the study presented here) compared with the length of the individual cardiac cycle.

How does their long time interval method perform? In a retrospective evaluation of their algorithm, the authors report root-mean-squared-normalized errors of 15.3% and 15.1% when comparing their relative cardiac output estimates with thermodilution (radial artery blood pressure data set) and Doppler ultrasound measurements (noninvasive finger-cuff photoplethysmography data set), respectively. For the clinical community, it is worth pondering whether these results, along with the benefit of having a continuous measure of relative cardiac output changes, already warrant the method's consideration for clinical application.

How do these numbers compare with other studies of invasive and noninvasive estimation of cardiac output from arterial blood pressure waveforms? The straightforward answer to the question is that such a comparison is not possible unless the performance of these algorithms is tested on the same data set. Lu and Mukkamala have taken a first step in the right direction by demonstrating that their long time interval method significantly outperforms simple curve fitting of the diastolic portion of the arterial blood pressure wavelet to obtain the windkessel time constant. However, a systematic comparison of all noninvasive cardiac output estimation algorithms is desirable. Because the authors have chosen to evaluate their algorithm on the publicly available Multi-Parameter Intelligent Patient Monitoring for Intensive Care (MIMIC) database (3), the possibility for such a formal comparison at least exists, although it must be emphasized that the MIMIC database is far from a reference database for such comparative purposes.

And so it seems that the field of continuous cardiac output estimation based on arterial blood pressure currently finds itself in a situation similar to what characterized the state of automated arrhythmia detection in the late 1970s: plenty of algorithms—some old, some new, some very elegant, and some packaged into commercial products—and most of them tested in retrospective and prospective clinical trials. Yet the developers and users cannot possibly compare the performance of one method with that of another, given that the algorithms have been tested on different, and in many cases sparse, data sets. The lesson to be learned from the arrhythmia community is the imperative need for a rich public database that can help in the evaluation of existing algorithms and the development of new ones. The potential benefits of such a public reference database can hardly be overestimated (5). This reference database should ideally draw data from all clinical fields (emergency care, intensive care, perioperative care, combat casualty care, etc.) in which such algorithms are to be employed.

Despite over 100 years of work on cardiac output estimation based on arterial blood pressure, we find that highly invasive, intermittent thermodilution-based cardiac output measurements have yet to be replaced as the de facto clinical gold standard. The long time interval approach presented by Lu and Mukkamala is novel and quite elegant; its assumptions and results certainly deserve the attention, and scrutiny, of the scientific and clinical communities.

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