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Gerard R. Manecke, Jr, MD
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Transcardiopulmonary Thermodilution-Calibrated Arterial Waveform Analysis: A Primer for Anesthesiologists and Intensivists

Nicola S. Laight, MBChB, and Andrew I. Levin, MBChB, DA, MMed (Anes), FCA, PhD

USE OF THE pulmonary artery catheter, the current clinical gold standard for cardiac output (CO) measurement,[1–4] is declining rapidly particularly outside cardiothoracic surgery.[5,6] One frequently quoted reason for this decline – that the device is too invasive – has coincided with the development of "less invasive" CO measurement techniques for monitoring of early goal-directed hemodynamic therapy (EGDT).[3,7–9] One of these less invasive techniques is transpulmonary (or transcardiopulmonary) thermodilution-calibrated arterial waveform analysis ($CO_{TPTD\text{-}AWA}$).[10–13] $CO_{TPTD\text{-}AWA}$ devices contain 2 separate technologies: (1) transcardiopulmonary thermodilution (CO_{TPTD}) for calibration, which is linked to (2) mathematical analysis of the arterial pressure-time waveform for continuous CO estimation (CO_{AWA}) (Fig 1).

The numerous publications describing use of this technology indicate that it is gaining rapid acceptance as a physiologic monitor[9,13–37] and as a reference standard in research.[38–41] Its scientific applications have included monitoring of lung water and fluid therapy in acute lung injury[36,42–62]; physiologic monitoring in adult[18,19,63–67] and pediatric[68–71] cardiac surgery and hepatic surgery[72–75]; and monitoring of critically ill pediatric[76–81] and adult patients with burns,[82–84] sepsis,[85–88] and intracranial pathology.[89–93]

$CO_{TPTD\text{-}AWA}$ and the derived additional hemodynamic parameters employ elusive processes to derive CO.[8,10–13,94] To appreciate the possible uses, advantages, limitations, and potential inaccuracies of research incorporating this emerging technology, the practitioner requires an understanding of the principles underlying $CO_{TPTD\text{-}AWA}$.[95]

The principles underlying CO_{TPTD} are similar to CO estimation using a thermodilution pulmonary artery catheter (CO_{PAC}) (Fig 2).[10,11,96,97] In both techniques, a bolus of saline colder than body temperature is administered via a central venous catheter. A downstream thermistor-tipped catheter, located in the pulmonary artery with CO_{PAC} and in close proximity to the aorta with CO_{TPTD}, detects the consequent temperature change.

Performing CO_{TPTD} requires insertion of a central venous catheter and a thermistor-tipped arterial catheter; the latter is inserted close to or in the aorta. Iced saline boluses (usually 10-20 mL in adults) are injected via the central venous catheter. The consequent arterial temperature decrease is detected by the arterial thermistor. The "thermodilution" curve is used to estimate CO. Typically, 3 thermodilution CO determinations are averaged to provide a reference CO estimation. A separate but linked system mathematically uses this reference CO and mathematical analysis of the arterial pressure-time waveform to calculate CO continuously (Fig 1).

$CO_{TPTD\text{-}AWA}$ frequently is called PiCCO (pulse index continuous cardiac output), which refers to specific commercially available technology (PULSION Medical Systems SE, Feldkirchen, Germany) that is available either as a stand-alone or a modular device; the latter is compatible with physiologic monitors from various manufacturers (Philips, Andover, MA; GE Healthcare, Chalfont St. Giles, United Kingdom; Drägerwerk AG, Lübeck, Germany; Shenzhen Mindray Bio-Medical Electronics, Shenzen, China; Maquet, Rastatt, Germany). PiCCO technology has been available for more than a decade, and similar technology (VolumeView and EV1000; Edwards Lifesciences, Irvine, CA) has become available more recently for clinical use. For the sake of impartiality, the authors refer to the techniques as $CO_{TPTD\text{ -}AWA}$ wherever possible.

ARTERIAL WAVEFORM ANALYSIS: COMPUTING FLOW FROM PRESSURE

More than 100 years ago, physiologists Frank and Erlanger independently stated that pulse pressure was related to stroke volume.[98] Frank developed the Windkessel model of the circulation with the explicit purpose of deriving blood flow from arterial pressure; this method is still the basis of arterial CO_{AWA}.[94] However, the long history attests to the difficulties encountered while translating the physiologist's principles into the recently developed, accurate measurement of CO.[99,100]

The original pulse contour method attempted to derive stroke volume by dividing the area under the systolic aortic pressure-time relationship by (a pressure- and heart rate-corrected value of) aortic impedance.[21,100–105] This method contained a major flaw in that aortic compliance was assumed to be a constant and independent of aortic pressure.[94,106] Wesseling's group identified this flaw. They studied 45 excised

From the Department of Anesthesiology and Critical Care, University of Stellenbosch, Tygerberg Hospital, Cape Town, South Africa.

Address reprint requests to Andrew Levin, MBChB, DA, MMed (Anes), FCA, PhD, Department of Anesthesiology and Critical Care, University of Stellenbosch and Tygerberg Hospital, Room 2044, Clinical Building, Cape Town, Western Cape 7505, South Africa. E-mail: ail@sun.ac.za

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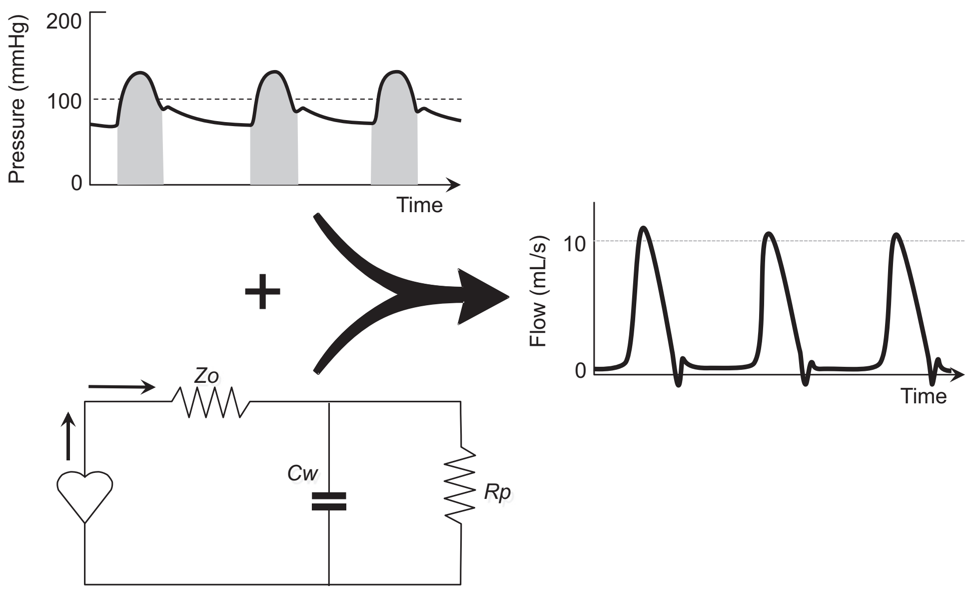

Fig 1. **The principles underlying the Modelflow method. The arterial pressure versus time waveform is transformed into a flow versus time relationship with input from the Windkessel model of the circulation.**

cadaver thoracic aortas and derived a mathematical formula that accurately described the relationship among aortic pressure, aortic diameter, and aortic compliance.[94,107–109] This formula permitted the development of the Modelflow technique,[94] the technology underpinning the PiCCO and EV1000 devices and certain other present-day CO_{AWA} techniques.[105] The Modelflow technique is more accurate than the pulse contour CO_{AWA} method, the accuracy (mean ± SD) of the 2 techniques being 2 ± 8% (Modelflow) and 6 ± 12% (pulse contour CO_{AWA}).

Understanding the complexity of the Modelflow CO_{AWA} method allows appreciation of the associated potential pitfalls and solutions. The Modelflow CO_{AWA} technique comprises 2 steps (Fig 1). The first step involves transforming the arterial

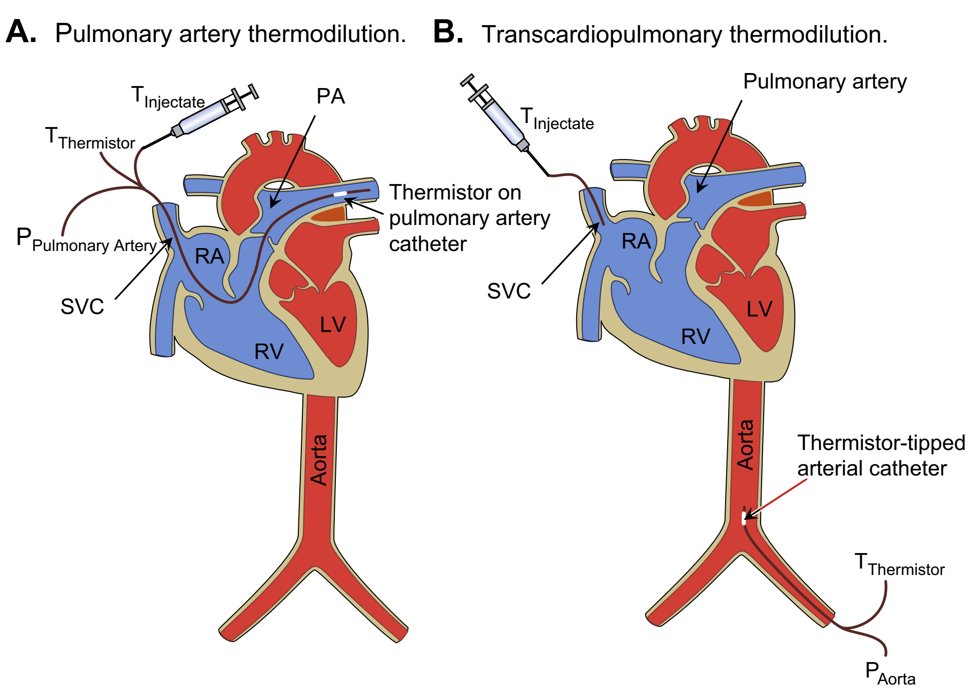

Fig 2. **Comparison of pulmonary artery (A) and transcardiopulmonary (B) thermodilution techniques. $T_{INJECTATE}$ and $T_{THERMISTOR}$ represent the measurement of injectate temperature at the sites of injection and at the pulmonary and aortic thermistors, respectively; $P_{PULMONARY\ ARTERY}$ and P_{AORTA} represent pulmonary artery and aortic pressures, respectively. LV, left ventricle; RA, right atrium; RV, right ventricle; SVC, superior vena cava.**