Transpulmonary Thermodilution

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7.1 Introduction

The optimal management of the critically ill patients demands precise and continuous monitoring of multiple clinical parameters. Over the past decades, the transpulmonary thermodilution technique (TPTD) has gained a wide application in the ICU settings and partially replaced pulmonary artery catheter (PAC) in the area of advanced hemodynamic monitoring. This technique integrates a variety of static and dynamic hemodynamic parameters. The knowledge of TPTD variables and of those obtained with the pulse contour analysis after calibration by thermodilution can help in the decision-making process in shock, ARDS, severe trauma, burn injuries, and high-risk surgical procedures. The TPTD is less invasive compared to PAC and provides relevant information regarding cardiac output, preload, systolic function, and lung edema.

7.2 Methodology

The TPTD requires a central venous access and a specific thermistor-tipped arterial catheter, which is usually inserted into the femoral artery. During thermodilution, a known volume of a cold indicator, typically 0.9% saline, is injected into the vena cava *superior* or the right atrium, mixing with the blood flow in the right heart, pulmonary circulation, left heart, and aorta. An arterial thermistor-tipped catheter records the changes in circulating blood temperature and generates a thermodilution curve. The cardiac output (CO) can be calculated

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from the area under thermodilution curve using the Stewart-Hamilton equation:

$$CO = K \times V_{inj} \times \left(T_b - T_i\right) / \int \Delta T_b \times dt$$

where K is the correction constant, V_{inj} is the injectate volume, T_b is the blood temperature, T_i is the injectate temperature, and $\int \Delta T_b \times dt$ is the integral of the temperature change over time (reflecting area under thermodilution curve).

The measurement of CO by TPTD serves as a calibration value for the calculation of CO derived from the arterial pulse contour waveform, which allows continuous (beat-to-beat) CO monitoring. The methodology of transpulmonary thermodilution measurements is described in detail in Table 7.1 and Fig. 7.1.

In addition to CO, several volumetric variables including global end-diastolic volume

Table 7.1 Calculation of the selected transpulmonary thermodilution-derived hemodynamic variables

Variable	Calculation
Intrathoracic thermal volume (ITTV)	CO × MTt
Pulmonary thermal volume (PTV)	CO × DSt
Global end-diastolic volume (GEDV)	ITTV–PTV
Intrathoracic blood volume (ITBV)	1.25 × GEDV [1]
Stroke volume (SV)	CO/HR
Global ejection fraction (GEF)	(4 × SV)/GEDV
Cardiac function index (CFI)	CO/GEDV
Cardiac power index (CPI)	MAP × CO
Extravascular lung water (EVLW)	ITTV–ITBV
Pulmonary blood volume (PVB)	ITBV–GEDV
Pulmonary vascular permeability index (PVPI)	EVLW/PBV

CO cardiac output, *MTt* mean transit time, *DSt* downslope time, *HR* heart rate, *ITTV* intrathoracic thermal volume, *PTV* pulmonary thermal volume, *GEDV* global end-diastolic volume, *EVLW* extravascular lung water, *PVPI* pulmonary vascular permeability index, *PBV* pulmonary blood volume, *ITBV* intrathoracic blood volume, *MAP* mean arterial pressure

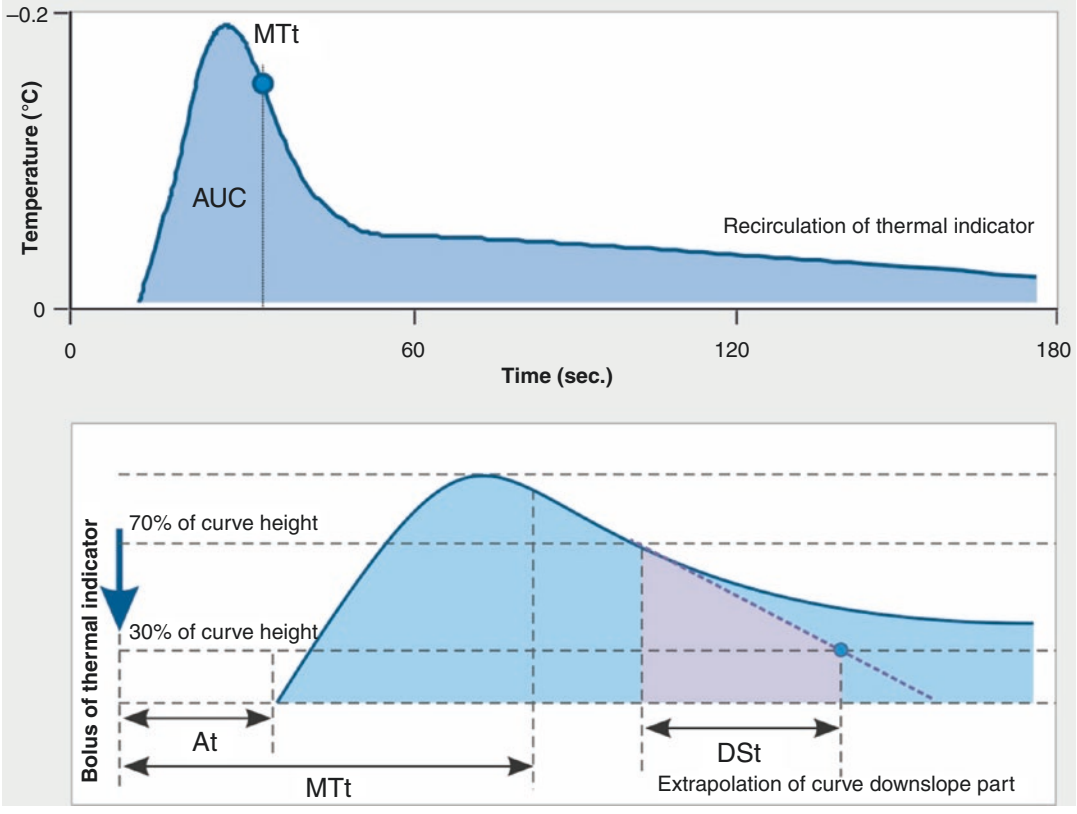

Fig. 7.1 The transpulmonary thermodilution curve and mathematical analysis. The mean transit time (*MTt*) is the mean time required for the indicator to reach the detection point at the tip of the arterial catheter (mostly positioned in the femoral artery) and the downslope time (*DSt*) is the exponential decline time of the thermodilution curve. *At* appearance time, *AUC* area under curve

(GEDV) and extravascular lung water (EVLW) can be readily measured and calculated from the mean and downslope times of cold indicator (see Chaps. 12–14). The values of several TPTD-derived variables are indexed for body weight or surface area, while recent models of monitoring systems use predicted body weight (PBW) and predicted body surface area (BSA) for the personalized volumetric management.

Today, two TPTD devices are commercially available: the PiCCO system (PULSION Medical Systems, Feldkirchen, Germany), now integrated into the PulsioFlex platform (Getinge, Gothenburg, Sweden), and the VolumeView™ system, which is incorporated in the EV1000 platform (Edwards Life Sciences, Irvine, USA) [2]. In addition, Philips, Dräger, Mindray, Nihon Kohden and GE have modules allowing to use the PiCCO arterial catheter and central venous catheter injectate device with their monitoring systems. Figure 7.2 demonstrates the schematic view of the system for TPTD.

Several important steps should be followed for the correct bedside application of TPTD. These steps are also shown at electronic supplementary material (courtesy of Drs. Evgenia V. Fot and Dmitry A. Svirsky, Department of Anesthesiology and Intensive Care Medicine, Northern State Medical University, Arkhangelsk, Russian Federation):

- Check and input correctly the biometric parameters (weight, height, gender).
- Perform a visual assessment of the arterial waveform, and perform a rapid flush test by ejecting a small volume of thermal indicator into the arterial catheter. The square waveform generated after the test has been suggested as a suitable method for determining the adequate dynamic response characteristics of the monitoring system.
- Place the pressure transducer at the phlebostatic axis (at the level of the right atrium), and zero the system against the ambient pressure.
- Measure and enter the central venous pressure for the calculation of the systemic vascular resistance.
- Prepare the correct solution for bolus injection. It is recommended to use 0.9% normal saline with a volume of 0.2 mL/kg (maximum

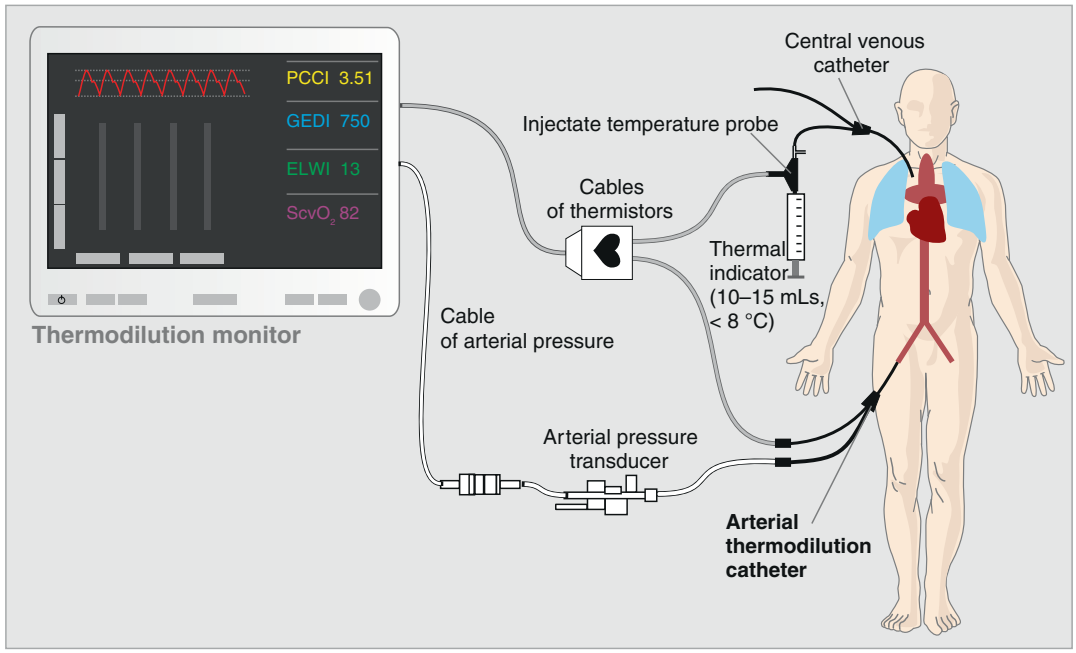

Fig. 7.2 The schematic presentation of the transpulmonary thermodilution

20 mL)—usually 15 mL for adult patient. It is important to inject the exact amount that was pre-set on the monitor. For the correct measurement of EVLW, the injectate temperature should be less than 8 °C [3].

- Injection should be performed in the most distal lumen of the central venous catheter, and the connection should be as close to the patient as possible. A fast and steady injection is recommended at a speed of >2.5 mL/s. The whole bolus hence should be injected for less than 6 s for a 15 mL [4].
- Perform the assessment of the TPTD curve. A typical TPTD curve has a flat portion, which reflects the transit time of the cold injectate from the injection site to thermistor, followed by a rise and fall in $\Delta T°$ with an exponential decrease, ending by a plateau due to physiological recirculation of the indicator.
- A series of at least three cold boluses is needed to obtain an adequate precision of the measurements [2]. A single measured value of CO should not deviate by more than 15% from the mean value. The same is true for GEDVI and EVLWI.

The most common conditions and sources of the erroneous measurements leading to the incorrect results of TPTD are listed in Table 7.2.

The specific limitations of the TPTD should be recognized. If cardiac index is severely decreased (typically, below 1.5–2.0 L/min/m^2), particularly, in combination with a relatively low heart rate, TPTD may not provide any reliable results because of prolonged thermodilution curve. Another limitation of TPTD for measuring CO is that it performs only intermittent measurements. The continuous "beat-to-beat" pulse contour analysis provides real-time monitoring of CO, although calibration must be performed every 6–8 h during the steady state or every time, when CO is needed for interpreting the

Table 7.2 Common conditions and errors influencing on variables obtained with transpulmonary thermodilution

Source of error	Comments
Incorrect technique of injection	An interrupted injection can cause the thermodilution curve to be bifid with over- or underestimation of the volumetric indices If the femoral vein is used for injection, all TPTD values like CO, GEDVI, and EVLWI are increased, due to the longer transit time of the indicator and the augmented volume participating in thermodilution. The femoral arterial catheter should not be inserted on the same side as the femoral vein catheter [5] The room temperature of injectate leads to a systematic overestimation of CO, GEDVI, and EVLWI [3]
Shunts	Shunts influence the shape of the thermodilution curve. The TPTD can be a simple tool to diagnose and monitor the right-to-left intracardiac shunting in ARDS patients [6]. A left-to-right shunt is characterized by an early recirculation of the cold indicator responsible for a premature flattening of the descending portion of the curve, resulting in an increased mean transit time (up to 25%) and increased downslope time (up to 50%) and hence affecting EVLWI [7]
Effect of CRRT	Continuous renal replacement therapy has no major clinical impact with a small decrease in CO and GEDVI and a small increase in EVLWI [8]. The effects may be more pronounced if CO is low and the blood flow over the circuit is high [9]
Effect of ECMO	Marked increases in GEDVI and EVLWI after the onset of ECMO. CO and hemodynamic parameters not derived from TPTD are not affected by the extracorporeal circuit [10]. In other opinion, ECMO can be considered as a contraindication to TPTD [2]
Valvular disorders and heart function	Regurgitation of the thermodilution injectate can prolong the transit time of the indicator or interfere with the thermodilution curve. The long and flat running of the thermodilution curve may result in an overestimation in the GEDVI and EVLWI. Mitral regurgitation gives a consistent increase in the volumetric parameters, while aortic stenosis gives an inconsistent increase
Pleural effusion	The pleural effusion of large volume leads to an overestimation of EVLWI, because the cold indicator also diffuses in the pleural liquid [11]. Most recent data have questioned the serious influence of pleural effusion on the accuracy of TPTD [12]

Table 7.2 (continued)

Source of error	Comments
Pneumonectomy	The correct calculation of the CO and GEDVI is possible in patients after pneumonectomy. The underestimation of the EVLWI is dependent on the amount of lung resection, whereas the trend of the EVLWI remains accurate [13]
Pulmonary embolism	The GEDVI will be overestimated, while the EVLWI will be underestimated [14]. In the case of pulmonary embolism complicated with an opening of *patent foramen ovale* and transient right-to-left shunting, the "camel"-like thermodilution curve can be observed
Aortic aneurism	In patients with an aortic aneurysm and a femoral arterial catheter, GEDVI and ITBVI are overestimated due to the volume of the aneurysm; thus axillary, brachial, or a long radial catheter might be recommended [15]
Ventilator settings	The theoretical effects of PEEP on the measurement of EVLW by TPTD are contradictory [2]. The PEEP increase can directly result in the increase of EVLWI due to the blockade of lymphatic flow [16]. One-lung ventilation can affect estimation of EVLWI [17]

TPTD transpulmonary thermodilution, *CO* cardiac output, *GEDVI* global end-diastolic volume index, *EVLWI* extravascular lung water index, *ARDS* acute respiratory distress syndrome, *PEEP* positive end-expiratory pressure, *ECMO* extracorporeal membrane oxygenation, *CRRT* continuous renal replacement therapy

hemodynamic changes [18]. A specific limitation of GEDV is that it does not distinguish between left and right cardiac preloads. In practice, in the case of the right ventricular dilation, GEDVI is increased, while the left ventricular preload is normal [19, 20]. In patients with septic shock, GEDV increases along with fluid administration but remains constant during dobutamine administration despite increased CO [21]. It has been suspected that mathematical coupling exists between GEDV and CO since both variables are derived from the same thermodilution curve.

The TPTD is contraindicated in the case of femoral vascular prostheses (with the radial or axillar arteries as possible alternatives for the femoral insertion site) and, plausibly, extracorporeal membrane oxygenation [2, 22]. Since TPTD needs catheterization of the artery and central vein, the procedure requires evaluation of the coagulation profile including platelet count, fibrinogen, international normalized ratio, and activated partial thromboplastin time. As has been shown in a multicenter trial, TPTD can be accompanied by minor problems such as oozing after insertion (3.3%) or the removal of the catheter (3.5%), small local hematomas after insertion (4.5%) and after the removal (1.2%) of the catheter, site inflammation (2%), catheter-related infection (0.78%), ischemia (0.4%), pulse loss (0.4%), or femoral artery thrombosis (0.2%) [23]. However, the use of TPTD catheters did not increase the risk of complications when compared with the commonly used short peripheral arterial catheters or PAC [23]. Thus, the risk of possible complications of TPTD should be weighed against the severity of the patient condition and possible benefits. Therefore, TPTD is justified, first of all, for high-risk surgical or critically ill patients [24] and recommended by the European Society of Intensive Care Medicine as a part of the current standard for managing shock and ARDS [25].

7.3 Conclusions

The TPTD is an advanced monitoring technique providing complex view into the hemodynamic profile of the patient at the bedside. Being less invasive compared with pulmonary arterial catheter, TPTD is safe in the overwhelming majority of cases if take into account the indications and contraindications for the procedure. In addition to the assessment of cardiac output, TPTD provides a wide spectrum of clinically relevant hemodynamic parameters characterizing preload, contractility, fluid status, and vascular permeability. However, before using TPTD, the clinician should be aware of the fact that none of the monitoring systems are able to improve patient outcome unless coupled with an appropriate treatment algorithm utilizing the evidence-based interventions and personalized patient care.

Keynotes

- Transpulmonary thermodilution is an invasive technique of bedside volumetric hemodynamic monitoring providing valuable information regarding cardiac output, global contractility, preload status, lung edema, and vascular permeability.
- The strict and thorough adherence to the technical requirements is of paramount importance to provide clinically plausible and reproducible measurements.
- Specific conditions, clinical scenarios, and technical errors may result in either overestimation or underestimation of TPTD-derived parameters.
- Further studies of "patient-specific" values of the parameters obtained by TPTD and algorithms of personalized management are warranted.

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