

THE INFLUENCE OF LIMITED DYNAMIC RESPONSE OF THE INDICATOR DETECTOR IN A SWAN-GANZ CATHETER ON THE OVERESTIMATION OF CARDIAC OUTPUT MEASUREMENT BY MEANS OF THERMODILUTION

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Abstract

Nowadays the “gold clinical standard” of hemodynamics diagnostic and cardiac output measurements is pulmonary artery catheterization by means of the Swan-Ganz catheter and thermodilution. The method itself is sensitive to numerous disturbances which cause inaccurate results. One of the well-known disadvantages of thermodilution is the overestimation of results at low values of cardiac output. This effect may concern the limited slew rate of the thermoelement mounted at the tip of the catheter. In this paper the relationship between the dynamic response of the thermoelement and the uncertainty of cardiac output measurements by means of thermodilution has been investigated theoretically and experimentally.

Keywords: cardiac output measurement, thermodilution method, Swan-Ganz catheter.

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1. Introduction

Apart from intracardiac pressures, the cardiac output (CO) constitutes one of the most important hemodynamics parameters [1, 18]. In spite of numerous non-invasive methods of CO measurements (e.g. blood flow generated by ventricular assist devices [2-3] or image-based methods [17]) in the course of the last 40 years, thermodilution has achieved considerable clinical significance [1, 4]. The examination runs as follows: first a Swan-Ganz catheter is placed into a vessel of the pulmonary circulation (this procedure is called pulmonary artery catheterization – PAC). Next, the indicator (most often 10 ml of iced or room-temperature 0.9% NaCl) is injected through the catheter into the right atrium. The indicator is diluted by flowing blood and transferred through the right ventricle and pulmonary trunk to a detector located at one of the pulmonary arteries. A miniaturized thermoelement is applied as the detector in the Swan-Ganz catheter. The detector is connected to the patient’s monitor, which measures and registers the temperature of blood vs. time characteristics, called the indicator dilution curve (IDC – see Fig. 1). The CO is calculated based on the Stewart-Hamilton (1) and the registered IDC .

$$Q = \frac{c_i \cdot \sigma_i}{c_b \cdot \sigma_b} \cdot \frac{V_i \cdot (T_{b0} - T_i)}{\int_0^{\infty} T_b(t) dt}, \quad (1)$$

where: c_b , c_i – specific heat of blood and the indicator, ρ_b , ρ_i – mass density of blood and the indicator, V_i – volume of the indicator, T_{b0} , T_i – temperature of blood and the indicator, $T_b(t)$ – indicator dilution curve.

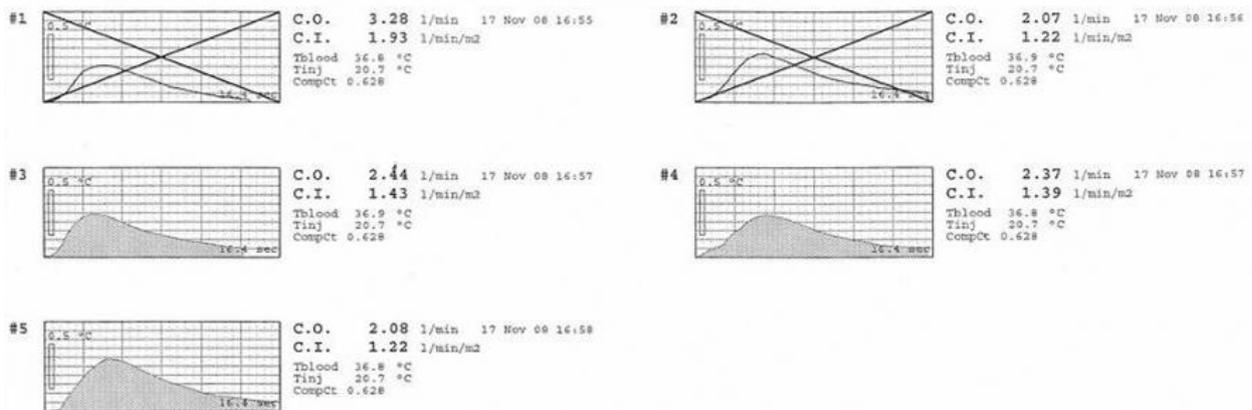


Fig. 1. The hemodynamics report of CO measurements by means of thermodilution in a patient with cardiac insufficiency – demonstration of the curves of the indicator dilution (IDC).

The results of CO measurements by means of thermodilution are sensitive to numerous disturbances with a different physical nature. It has been pointed out in many papers [1, 5-7] that the most significant reasons of the uncertainty of thermodilution are: inaccuracy of measurements of the indicator and blood temperature, instability of the volume of the indicator, variable thermodynamic parameters of blood (*e.g.* caused by intravenous injection of medicines), diseases of the valves, intracardiac leaks of blood, spontaneous ventilation, arrhythmia, displacement of the catheter during the examination and thermal instability of the patient (*e.g.* hypothermia or an inflammatory state [8]). In spite of invasiveness and the problems mentioned above, PAC and CO measurements by means of thermodilution provide many valuable hemodynamics data and constitute the “gold standard” of hemodynamic diagnostics [1, 18].

A clinically well-known disadvantage of thermodilution is the overestimation of the results of examinations in the case of low values of CO [9-11]. The meaning of this problem is particularly important in the case of patients with serious heart failures connected with cardiac contractibility impairment and decrease of ejection fraction and cardiac output. Overestimation of CO may in those patients leads to incorrect diagnosis and, in consequence, contributes to taking a wrong decision concerning further therapy.

Up till now the cause of the problem mentioned above has not been unambiguously explained. One possible reason seems to be limited dynamic response of the detector of the indicator concentration, namely the thermoelement mounted at the tip of the Swan-Ganz catheter.

2. Goal

The goal of investigations was to assess the influence of the dynamic response of the detector on results of CO measurements by means of thermodilution and the Swan-Ganz catheter.

3. Material and methods

The following method of investigation has been assumed: the dilution process was mathematically modeled in order to determine the course of IDC . Next, by means of numerical differentiation the maximum value of the IDC slew rate (dT/dt) was calculated for different flows. Those data were compared with dT/dt measured experimentally for the thermoelement in the Swan-Ganz catheter.

Theoretical determination of the course of *ICD* was carried out by means of a mathematical, one-dimensional *Local Density Random Walk* model of dilution [12, 14]. The model allows to determine the way of indicator dilution inside a rectilinear vessel containing the flowing liquid. Numerous initial assumptions of this model are, among others: impulse injection of the indicator, constant velocity of flow, the Brownian movement of the molecules of the indicator and their ideal elastic collisions with the molecules of the liquid and the lack of dissipation of the indicator through the walls of the vessel. The mathematical definition of the *LDRW* model will be explained below.

The time dependence of the concentration of the indicator at the measurement point is defined by (2):

$$c(t) = \frac{m_i}{Q} \sqrt{\frac{\lambda}{2\Pi \cdot \mu \cdot t}} \cdot e^{-\frac{\lambda}{2} \left(\frac{t}{\mu} + \frac{\mu}{t} \right)}, \quad (2)$$

where: m_i – mass of the indicator, Q – volumetric flow, μ – mean transit time of the indicator between the point of injection and detection, λ – nondimensional skewness coefficient.

The mean transit time of the indicator is calculated by means of (3):

$$\mu = \frac{x}{Q} \cdot A, \quad (3)$$

where: x – distance between points of injection and measurement, A – the cross-section area of the vessel.

The skewness coefficient λ (4) concerns the Peclet number, which defines the ratio of the thermal diffusive flow to the convective flow:

$$\lambda = \frac{\mu \cdot Q^2}{2 \cdot D \cdot A^2}, \quad (4)$$

where: D – the diffusion coefficient [m^2/s].

The diffusion coefficient (5) determines the ratio of the coefficient of thermal conductivity [$\text{J}/(\text{s} \cdot \text{m} \cdot \text{K})$] to the volumetric thermal capacity [$\text{J}/(\text{m}^3 \cdot \text{K})$]. Usually the diffusion coefficient has to be determined experimentally.

$$D = \frac{R_T}{C_V} = \frac{R_T}{c_w \cdot \rho}. \quad (5)$$

Numerical simulations of the course of *IDC* were carried out for flow in the range of 1.0 – 5.0l/min and for two areas of the cross-section of the vessel: 3 cm^2 and 4 cm^2 . The maximum value of the *IDC* slew rate was calculated by means of numerical differentiation.

Experimental investigations were carried out on the Swan-Ganz catheter (size 7F, Becton-Dickinson). The thermal excitation in the form of a negative temperature step was generated by a rapid plunge of the catheter into the liquid with a stabilized temperature, lower than the ambient temperature. The thermoelement mounted in the catheter was connected to a Wheatstone bridge and amplifier (Fig. 2) similar to the device applied in the patient's monitor (FX2000, Emtel). The registration of voltage (corresponding to temperature) was carried out by means of a multifunction data acquisition device with a sampling frequency of 1kHz (NI-USB-6221, National Instruments). Both temperatures, ambient and liquid, were measured by means of a precise electronic thermometer (Fluke 1532 and PRT probe, accuracy 0.001 $^{\circ}\text{C}$).

It was assumed that the voltage vs. the temperature transfer function is linear. This assumption is correct because at low increases of temperature the polynomial transmittance of the thermocouple may be approximated by a linear function with a low uncertainty. The

temperature vs. voltage scaling was carried out by appropriate measurements at two different temperatures (36.0°C and 37.0°C).

For all thermal excitations $N = 12$ measurements were carried out. Due to the unknown variance of statistical population and low sample size, Student's distribution ($p = 0.05$) was applied to the determination of confidence limits.

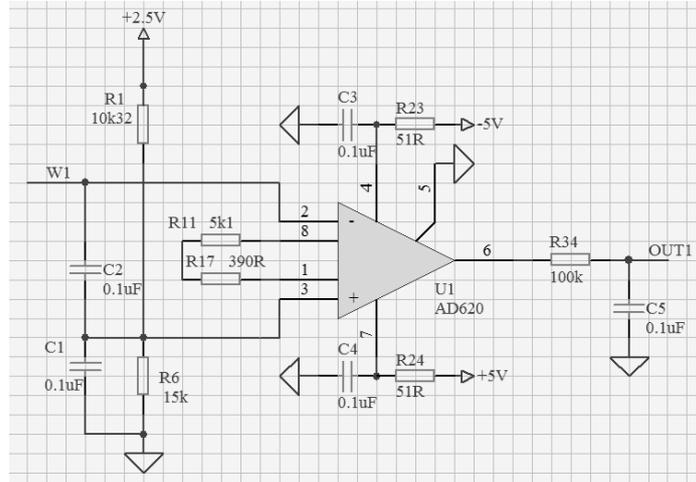


Fig. 2. Scheme of the measurement system.

4. Results

Numerical simulations of the course of IDC were carried out for flows in the range of 1.0...5.0l/min and for areas of the cross-section of the vessel amounting to 3.0 cm² and 4.0cm². The value of the diffusion coefficient $D=0.0500\pm 0.0035$ was estimated experimentally by analyzing the IDC curves collected during examinations of patients [12]. The demonstration courses of IDC and its derivative have been presented in Fig. 3 and Fig. 4, respectively. The dependence of dT/dt vs. flow is to be seen in Fig. 5.

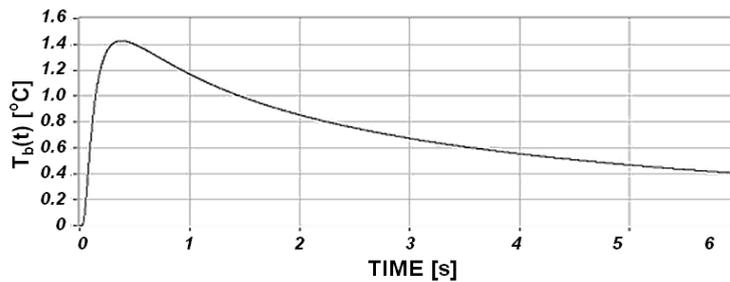


Fig. 3. The course of IDC (numerical simulation).

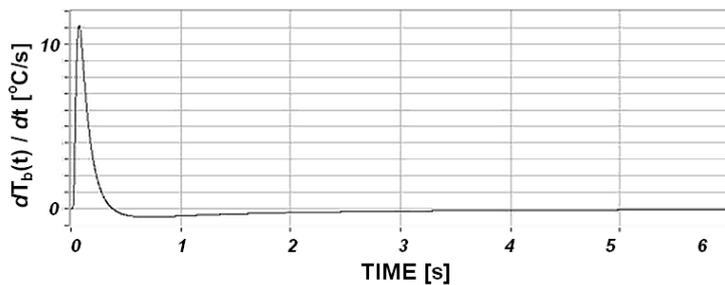


Fig. 4. The course of the derivative of IDC .

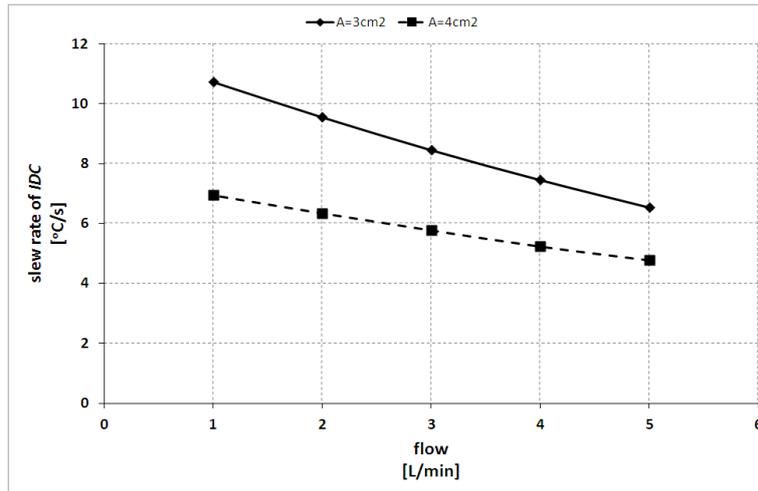


Fig. 5. Relationship between the maximum value of the IDC slew rate, the flow and cross-section area of the vessel.

Physical measurements of dT/dt of a thermoelement in the Swan-Ganz catheter were carried out for large values of negative thermal step excitations (Fig. 6 – solid line). The values of dT/dt at low thermal excitations were assessed by means of the regression method (Fig. 6 – dashed line).

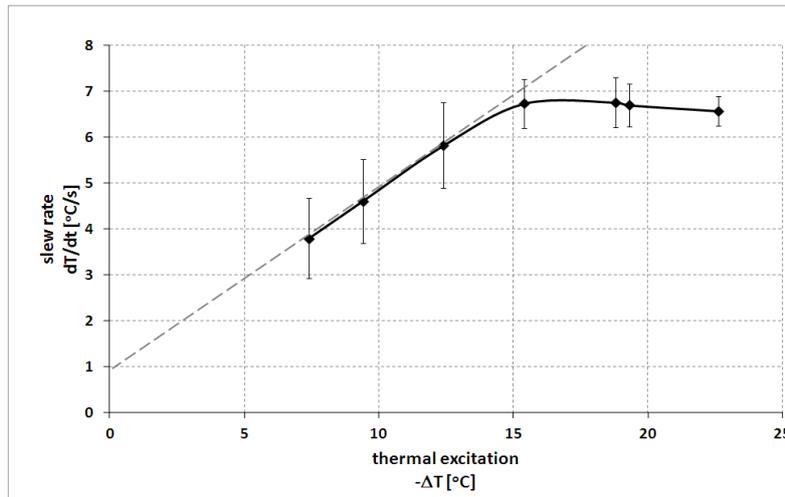


Fig. 6. The dependence of slew rate of thermoelement vs. amplitude of thermal step excitation.

For $-\Delta T < 15^\circ\text{C}$ the characteristic presented in Fig. 6 is linear and its slew rate amounts to 0.4s^{-1} . The dT/dt estimated for low amplitudes of thermal excitation by means of linear regression amounted to 1.0°C/s .

5. Discussion

There are very few papers concerning the dynamic properties of the thermoelement in the Swan-Ganz catheter. One of them claims that the time constant of the thermoelement amounts to 2s, however the authors did not inform about the conditions of the experiments, particularly about the value of thermal excitation [15]. Assuming the exponential model of phenomena quoted by (6), the maximum value of dT/dt calculated by differentiation of (6) at $t = 0$ amounts to 1.25°C/s (in the case of a typical temperature drop for iced thermodilution of

about 2.5°C). Physical measurements revealed that the dT/dt value for the investigated Swan-Ganz catheter and a similar temperature drop amounts to 2.0°C/s .

$$T(t) = (T_b - T_i) \cdot e^{-\frac{t}{\tau}} - T_i, \quad (6)$$

$$\left. \frac{dT(t)}{dt} \right|_{t=0} = -\frac{T_b - T_i}{\tau}. \quad (7)$$

Mathematical modeling of the course of ICD showed (Fig. 5) that dT/dt depends on the flow and area of the cross-section of the vessel with the following relationship: the lower the flow, the greater dT/dt . This effect was confirmed experimentally in measurements of CO by means of thermodilution carried out on the physical model of pulmonary circulation [12, 16]. The courses of IDC obtained for three values of flow (0.98, 1.81 and 2.40l/min) are presented in Fig. 7.

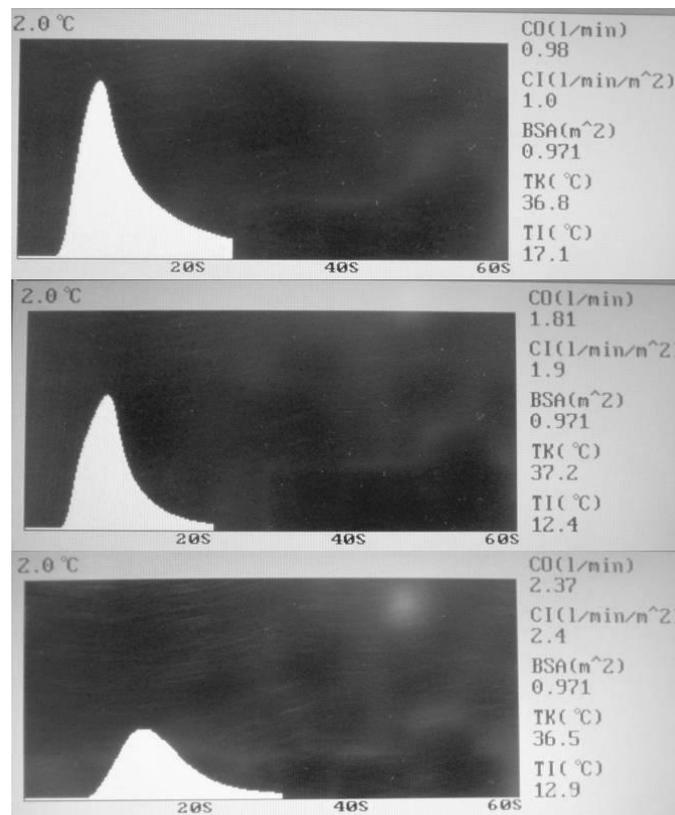


Fig. 7. Screenshots of the patient's monitor – CO measurements by means of thermodilution carried out on physical model of the pulmonary circulation.

Let us suppose that the area of the cross-section of the vessel amounts to 3 cm^2 and that the blood temperature drop after injection of the indicator amounts to 2.5°C (iced thermodilution). Under those conditions the theoretical dT/dt of IDC is in the range from 10.5°C/s to 6.5°C/s (for flows from 1.0l/min to 5.0l/min , respectively, see Fig. 6), but the dynamic response of the thermoelement in the Swan-Ganz catheter is significantly lower and amounts to 2.0°C/s (Fig. 5). This limitation causes a dynamic distortion of the IDC course which affects the value of the IDC integral and, in consequence, an uncertainty of CO measurements by means of thermodilution at low flows. The mechanics of this effect have been explained in Fig. 8. At a low CO the value of the slew rate in the initial part of IDC is much higher than the dynamic response of the thermoelement (e.g.: the performed investigations revealed that when

$CO=1.0\text{l/min}$, the theoretical dT/dt amounts to about 10°C/s and the slew rate of the thermocouple was 2.5°C/s . Due to the slower dynamic response of the thermoelement than the slew rate of IDC , the integral of the measured IDC is lower than the theoretical one (the difference has been marked in Fig. 8 in grey). Indeed, the lower the CO , the higher the underestimation of the integral of IDC . Because the integral of IDC is in the denominator of Stewart-Hamilton's equation (1), the decrease of this quantity leads to an overestimation of CO .

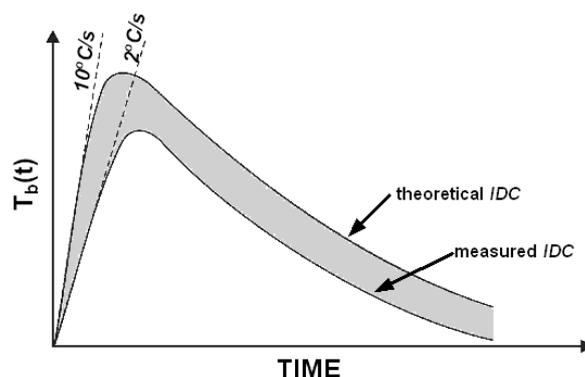


Fig. 8. Illustration of the influence of the slew rate of the temperature detector on the course and integral of IDC .

It should be noticed that even at a large diameter of the vessel and the value of CO , the slew rate of the thermodetector in the Swan-Ganz catheter is too low to measure IDC with appropriate dynamics. The effect of the dynamic response of the detector discussed in this paper influences significantly the uncertainty of all dilution methods, independently of the type of the indicator, and it seemed to be impossible to be compensated mathematically.

6. Conclusions

Basing on the performed investigations it may be said that one of the reasons of overestimation of the low cardiac output measured by means of thermodilution is the limited dynamic response of the thermoelement in the Swan-Ganz catheter.

Acknowledgements

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