Journal of Clinical and Nursing Research, 2026, Volume 10, Issue 6
http://ojs.bbwpublisher.com/index.php/JCNR
Online ISSN: 2208-3693
Print ISSN: 2208-3685

Flow Rate Control and Optimization of RCA Infusion System Based on ADRC and Two-Stage Calcium Supplementation Model

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Abstract: Based on the established two-stage mathematical model of Regional Citrate Anticoagulation (RCA), an automated RCA infusion system is constructed. Aiming at the flow rate accuracy problem of peristaltic pumps under variable pressure environments, a flow rate control algorithm based on Active Disturbance Rejection Control (ADRC) is designed, combined with pressure compensation and surface calibration methods. The experimental results show that this method can achieve high-precision infusion under different pressure differences and meet clinical requirements.

Keywords: RCA; ADRC; Flow control; Continuous renal replacement therapy

Online publication: Jun 30, 2026

1. Introduction

Safe and effective anticoagulation is the key technical difficulty of blood purification, especially for long-term Continuous Renal Replacement Therapy (CRRT). Regional Citrate Anticoagulation (RCA) has been proven to have an effective extracorporeal anticoagulant effect, which can avoid long-term exposure to heparin during continuous renal replacement therapy [1]. In addition to reducing the incidence of dialysis-related bleeding, RCA can also improve the service life of dialyzers and enhance their biocompatibility [2]. The internationally authoritative Kidney Disease: Improving Global Outcomes (KDIGO) organization issued clinical guidelines for acute kidney injury in 2012, recommending RCA as the preferred anticoagulation method for patients with acute kidney injury, especially those with hemodynamic instability, undergoing CRRT treatment [3].

The key technical point in the implementation of RCA is to determine appropriate infusion rates of citrate and calcium, so as to maintain the ion calcium concentration *in vivo* and extracorporeal circulation within a proper and narrow therapeutic target range. A mathematical model for predicting *in vivo* citrate concentration has been established in previous studies [4]. Based on this mathematical model, this study constructs a dual-pump automated RCA infusion system, explores the infusion precision technology of the RCA infusion system, and discusses flow rate control technology with the help of the test environment and test means of the Shanghai Institute of Medical Device Testing. The improved Active Disturbance Rejection Control (ADRC) algorithm is adopted to enhance the anti-interference ability of peristaltic pump flow precision [5–7]. Meanwhile, real-time compensation is performed for the infusion rates of citrate solution and calcium chloride solution, aiming at the complex positive and negative pressure differences before and after the pump, so as to improve infusion accuracy.

2. RCA infusion system

2.1. Hardware design

The structure of the RCA infusion system is shown in **Figure 1**. Its hardware system mainly includes a power supply, a main board, a storage battery, a motor, a touch screen, sensors, and other components. On both sides of the device are respectively equipped with citrate pump, bubble sensor, air pressure sensor, liquid level sensor, pinch valve, as well as calcium chloride pump, bubble sensor, liquid level sensor, and pinch valve. On the back of the device are the chassis fixing module, cooling fan air outlet, and external power interface. The device is internally equipped with lithium-ion storage batteries.

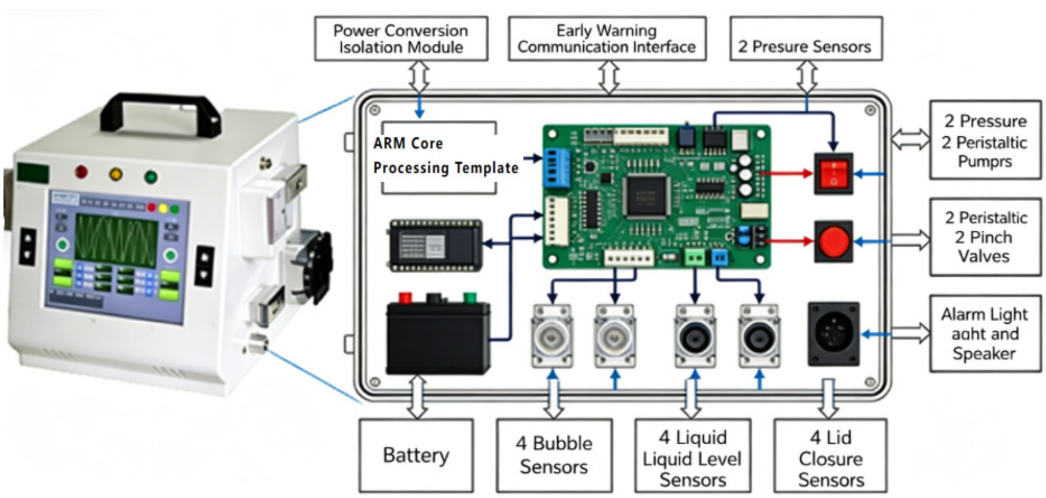

Figure 1. Composition of the RCA infusion system.

2.2. Software design

The core board adopted by the RCA infusion system runs the Debian 8.6 operating system. The main functions of the core board include operating the main program containing the two-stage model, processing sampling data, controlling actuators, recording data, and running the alarm monitoring module. The software structure is shown in **Figure 2**.

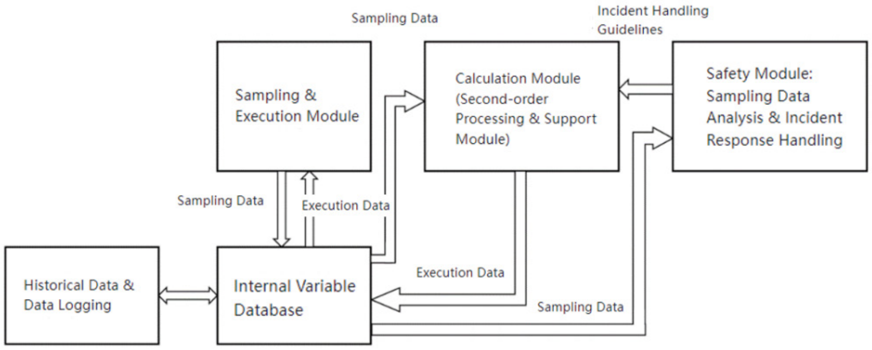

Figure 2. Schematic diagram of software structure.

3. Flow rate control and optimization based on the ADRC algorithm

3.1. ADRC design

The key indicator of the RCA infusion system lies in the infusion speed accuracy of the two peristaltic pumps. The infusion speed of the peristaltic pump is the most direct output of the two-stage theoretical model, which determines the core performance of the equipment. The peristaltic pump adopts a brushless DC motor matched with a machined pump head, enabling smooth and stable operation.

Figure 3 shows the basic structure of the second-order active disturbance rejection controller, where r represents the input, y represents the system output, k_p and k_d are the proportional coefficient and differential coefficient in the simplified PD control combination, ESO stands for Extended State Observer, and u is the control variable.

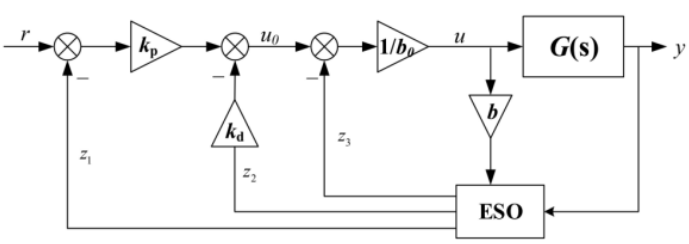

Figure 3. Structure diagram of the second-order linear active disturbance rejection controller.

The second-order controlled object G(s) is approximated according to the second-order active disturbance rejection controller:

$$\ddot{y} = f\left(y, \dot{y}, \omega, t\right) + bu = -a_1\dot{y} - a_0 y + \omega + bu \tag{1}$$

where y and u are output and input, respectively, and ω denotes disturbance. The parameter b contains a known part b_0, namely. $b = b_0 + \left(b - b_0\right)$. Select the state variables: $x_1 = y, x_2 = \dot{y}$, $x_3 = f$, then $x = [y \quad \dot{y} \quad f]^T$.

$$\begin{cases} \dot{x} = Ax + Bu + E\dot{f} \\ y = Cx \end{cases} \tag{2}$$

Where:

$$A=\begin{bmatrix}0 & 1 & 0\\0 & 0 & 1\\0 & 0 & 0\end{bmatrix},\ B=\begin{bmatrix}0\\b_0\\0\end{bmatrix},\ E=\begin{bmatrix}0\\0\\1\end{bmatrix},\ C=\begin{bmatrix}1 & 0 & 0\end{bmatrix}$$

The corresponding continuous linear extended state observer is:

$$\begin{cases}\dot{z}=Az+Bu+L\left(y-\hat{y}\right)=Az+Bu+L\left(y-Cz\right)\\ \hat{y}=Cz\end{cases} \tag{3}$$

where is the error feedback gain matrix of the observer, taken as:

$$L=\begin{bmatrix}\beta_1 & \beta_2 & \beta_3\end{bmatrix}^T=\begin{bmatrix}3\omega_0 & 3\omega_0^2 & \omega_0^3\end{bmatrix}^T \tag{4}$$

3.2. Pressure detection and compensation

The peristaltic pump is calibrated in the laboratory environment, with rotating speed as input and actual flow rate of standard liquid as output, and the calibration results show good repeatability. However, in the actual application environment, the output end of the peristaltic pump is connected to CRRT or iHD equipment. The citrate end is connected to the arterial end of CRRT/iHD, and the calcium chloride end is connected to the venous end of CRRT/iHD. The other ends of the two pumps are connected to the lead-out pipeline of human blood vessels, respectively. There is a pressure difference caused by the different front pump pressure P_f and rear pump pressure P_b, as shown in **Figure 4**.

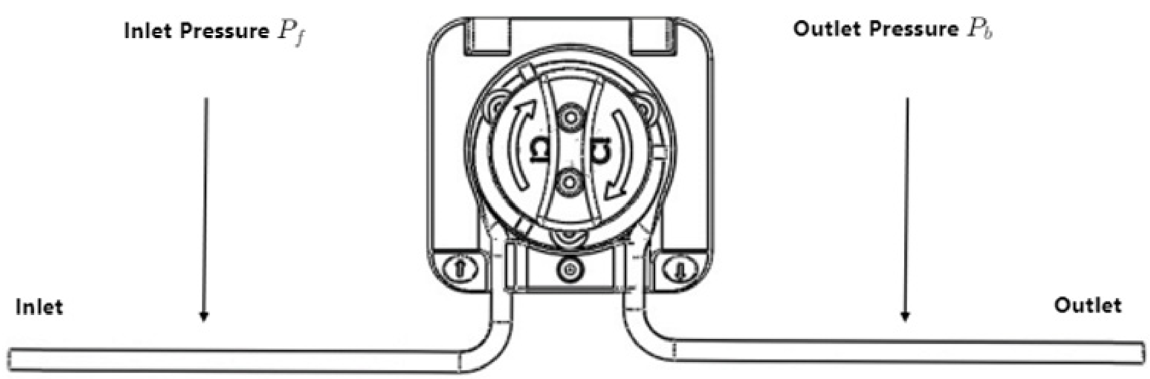

Figure 4. Pressure difference between the inlet and the outlet of the peristaltic pump.

The RCA infusion system must ensure an accurate infusion flow rate. In view of this problem, a pressure sensor is installed at the rear of the pump, and its sampling circuit is optimized to suppress zero drift, so that the pressure sensor can accurately measure the rear pump pressure. On the basis of pressure sensor signals, the flow rate of the peristaltic pump can be precisely controlled by accurately measuring the pressure difference between the front and rear of the pump and identifying its influence on flow rate.

The pressure sampling circuit adopts a fourth-order Chebyshev filter circuit (2nd order type). Its filtering response is shown in **Figure 5(a)**. The LM358 operational amplifier is used to suppress noise disturbance effectively. It has a good suppression effect on periodic interference with high smoothness, and its time lag fully meets the design requirements. The corresponding pressure signal curve is shown in **Figure 5(b)**, showing a good linear relationship with a correlation coefficient close to 1, which means the pressure sensor can accurately measure pipeline pressure.

When the front pump pressure is equal to the rear pump pressure, the relationship between peristaltic pump speed and actual liquid flow rate is shown in Figure 5(c). In actual operation, the peristaltic pump is calibrated in the surface form as shown in Figure 5(d). The calibration curve presents the corresponding relation in **Figure 5(c)** when $P=0$. When the pressure difference $P \neq 0$, the relation between the pump speed control signal and the flow rate is shown in Figure 5(d). It can be seen that the larger the absolute value of P, the greater the impact on actual flow rate; under the same pressure difference, the slower the control signal speed, the more obvious the impact. When $P \neq 0$, the actual flow rate is jointly determined by P and the control signal.

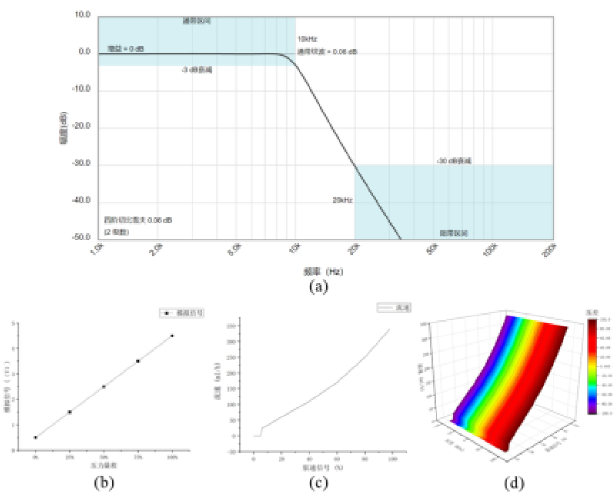

Figure 5. Results of air pressure acquisition. (a) Signal filtering; (b) Schematic diagram of pressure signal and corresponding output analog voltage; (c) Relationship between pump speed and liquid flow rate without pressure difference; (d) Relationship between pump speed and liquid flow rate with pressure difference

Therefore, the corresponding calibration relationship between the expected infusion flow rate of the RCA infusion system and peristaltic pump speed is a surface, as shown in **Figure 5(d)**, rather than a straight line or ordinary curve. A dual-fitting flow control algorithm is designed for this situation:

$$R_{flow} = f_1\left(sig\right) + f_2\left(\Delta P\right) \tag{5}$$

Where R_{flow} is the motor control output of the peristaltic pump; $f_1\left(\text{sig}\right)$ is the fitted value according to the calibration curve under the ideal condition of $\Delta \text{P}=0$, which is also the expected input of the ADRC algorithm; $f_2\left(\Delta \text{P}\right)$ Is the flow compensation corresponding to $\Delta \text{P} \neq 0$. $f_2\left(\Delta \text{P}\right)$ can be obtained by piecewise calibration combined with the least squares method.

4. Experimental results and analysis

Flow rate tests under various environments were completed in the laboratory of Shanghai Institute of Medical Device Testing, and the results are shown in **Table 1**.

Table 1. Relationship between compensated flow rate and peristaltic pump control signal under different pressure differences

Pressure difference ΔP (kPa)	Set flow rate (mL/h)	Control signal under ΔP = 0 (%)	Actual control signal (%)	Actual flow rate (mL/h)	Difference from ΔP = 0 (mL/h)
0	72.5	25	25	72.3	—
25	72.5	25	25.48	72.4	0.1
50	72.5	25	25.89	72.6	0.3
75	72.5	25	26.16	72.6	0.3
0	139.8	50	50	140.0	—
25	139.8	50	50.54	140.6	0.6
50	139.8	50	51.00	140.5	0.5
75	139.8	50	51.39	140.5	0.5
0	230.2	75	75	230.2	—
25	230.2	75	75.62	229.6	-0.6
50	230.2	75	76.04	229.5	-0.7
75	230.2	76.33	76.33	230.4	0.2

It can be seen from **Table 1** that under different pressure differences (), the compensated flow rate has little difference from that under , within the allowable error range of equipment technical requirements.

A tertiary hospital built an actual application environment by connecting the RCA infusion system with CRRT and other equipment for a series of tests, as shown in **Figure 6**. The three-necked flask at the bottom simulates the artificial pressure environment equipped with a pressure gauge, adopting a simulated test instead of a direct human test. The simulation results show that the RCA infusion system can work normally with infusion speed fully meeting equipment specifications and actual treatment requirements under pressure differences before and after the peristaltic pump.

Figure 6. Simulation test in a hospital treatment environment.

5. Conclusion and prospect

Aiming at the problems of the RCA infusion system in practical medical applications, this paper designs a peristaltic pump flow rate control system by adopting linear ADRC. To ensure accurate liquid infusion under a specific pressure difference and overcome regular errors caused by the external environment, the surface calibration method is adopted for flow compensation. Experimental results and actual hospital environment tests verify that the developed RCA infusion system can effectively improve flow rate accuracy, meet clinical requirements, and facilitate the clinical application of RCA technology.

Disclosure statement

The authors declare no conflict of interest.

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