Research on the Accuracy Control Technology of Automated Peritoneal Dialysis

Shiqiang Ge*

1 Jiangsu Automation Research Institute, Lianyungang, Jiangsu, 222061, PR China
*Corresponding author’s e-mail: ge_716@126.com

Abstract. The automated peritoneal dialysis is accepted increasingly. The automated peritoneal dialysis makes use of a device called automated peritoneal dialysis cycler to realize the automated treatment. The liquid quantity of dialysis treatment is an important index of peritoneal dialysis. Thus the flow calculation accuracy of the automated peritoneal dialysis cycler is one of the most important performances. However, due to the complex usage situations, the cyclers based on different principles are extremely affected by touching, flow resistance fluctuating, etc., which causes inaccuracy and instability. This paper investigated an accurate calculation model and a control algorithm to address these issues. Based on the State Equation of Ideal Gas, a calculation model is established. By analyzing the influence factors of time-varying flow resistance, a control algorithm is designed. A prototype with our method is developed and tested by experiments. The results show that the flow calculation errors are reduced significantly and the accuracy and stability are improved obviously. It proves that our method can realize an accurate flow calculating and effectively reduce errors and keep accuracy stable.

1. Introduction
Peritoneal dialysis (PD) is now a widely accepted, effective form of renal replacement therapy for patients with end-stage renal disease [1-2]. The continuous cycling PD (CCPD), also referred to as automated PD (APD), using the cycler, is popular [3-4]. Because of the good therapeutic effect and the convenience of performing dialysis overnight while asleep, the percentage of patients on APD is trending upward [5-6]. According to the principle, APD cyclers are broadly divided into weighing type and pneumatic driven type [7-9]. The weighing type APD cyclers use scales to weigh the initial and final values of the dialysate, and then calculate the difference as the treatment data. The Peritoneum IVTM (B. Braun, Germany), the Peritokomb IIIA TM (Fresenius, Germany), the Drake Willock 6001TM (Drake Willock, US), the FM-II TM (MEDA, China), etc, are of weighing type[7-8]. But some unavoidable interference, such as artificial operation, dialysis bag not in place, dialysate tube pulled out, etc., will lead to low accuracy. The pneumatic driven type APD cyclers use the Ideal Gas Equation to calculate the dialysate driven piston’s volume, then calculate the volume of piston motion each time and sum the volumes up as the treatment data [2, 9]. The HomeChoice TM (Baxter, US), the JARI-APD-1TM (JARI, China), the LibertyTM cycler (Fresenius, Germany), are of pneumatic driven type [2, 9, 11]. This type of APD cycler has a high-precision characteristic in the general case. However, if the height of patient's abdominal cavity changes during treatment, the flow resistance changes as the liquid level fluctuates. In this case, the accuracy error of these APD cyclers will be large [9-10]. It is very uncomfortable if the patient cannot move freely during treatment.
In this paper, based on the research of the Ideal Gas Equation, a new accurate control technology of pneumatic driven APD cycler was proposed. This technology can calculate the dialysate flow in real time, improve the flow accuracy and keep the accuracy stable.

2. Calculation model of dialysate flow
The pneumatic driven APD cycler uses disposable cassette with chambers and valves to drive the dialysate to flow [2, 9]. The cassette is loaded into the cycler. During the treatment cycle, the dialysate flows purely in the cassette and pipeline to ensure that the dialysate is not in contact with the APD cycler or outside world. The APD cycler system applies negative air pressure to the soft plastic membrane and pulls solution into the cassette chamber. The system then applies positive air pressure to the soft plastic membrane and pushes solution out of the chamber. The system applies pressure alternatively to the chamber so that the solution continues to flow. The model was built as shown in figure 1. We named it the soft-membrane-pump (SMP).

As shown in figure 1, the air chamber of the SMP was divided into two parts by the valve. The left side was defined as the reference chamber (VS1). The right side was defined as the performance chamber (PA1). The right side of the soft plastic membrane was defined as the pump chamber (P1). The State Equation of Ideal Gas is given as

\[ nRT = pV \]

where \( n \) is the amount of substance, \( R \) is the constant of the ideal gas, \( T \) is the thermodynamic temperature of the ideal gas, \( P \) is the pressure of the ideal gas, \( V \) is the volume of the ideal gas.

The steps of using the State Equation of Ideal Gas to calculate the dialysate flow are as follows.

Step 1: Close the valve, as shown in figure 2, apply negative air pressure to the PA1 and pull solution into the P1. Then disconnect the negative air pressure when it is stable and keep the PA1 sealed. Close the P1 to keep the solution unchanging in it.

Step 2: Connect the VS1 to the atmosphere. Then disconnect it when the pressure is stable.

Step 3: Measure the pressures of the VS1 and the PA1. The pressure of the VS1 is recorded as \( IP_{s1} \) and the pressure of the PA1 is recorded as \( IP_{p1} \). The volume of VS1 is \( V_s \) which is as a reference and a known quantity. The volume of PA1 is \( V_i \) which is the required value. According to (1), the equation can be expressed as

\[ IP_{s1} \times V_s + IP_{p1} \times V_i = nRT \]

Step 4: As shown in figure 3, open the valve so that the VS1 and the PA1 are connected. When the pressure is stable, measure the pressures of the VS1 and the PA1. The pressure of the VS1 is recorded as \( IP_{s2} \) and the pressure of the PA1 is recorded as \( IP_{p2} \). Then the equation can be expressed as

\[ IP_{s2} \times V_s + IP_{p2} \times V_i = nRT \]
Combining (2) and (3), the equation can be expressed as

\[ IP_{d_1} \times V_i + IP_{s_1} \times V_s = IP_{d_2} \times V_i + IP_{s_2} \times V_s \]  

(4)

The volume of PA1 can be calculated as

\[ V_i = \frac{(IP_{s_1} - IP_{s_2}) \times V_s}{IP_{d_2} - IP_{d_1}} \]  

(5)

Figure 2. Solution pulled and valve closed. 

Figure 3. Solution pulled and valve opened.

Step 5: Close the valve, as shown in figure 4, apply positive air pressure to the PA1 and push solution out of the P1. Then disconnect the positive air pressure when it is stable and keep the PA1 sealed. Close the P1 to keep the solution unchanging in it.

Step 6: Repeat steps 2 to 3. The pressure of the VS1 is recorded as \( FP_{s_1} \) and the pressure of the PA1 is recorded as \( FP_{s_1} \). The volume of PA1 is \( V_f \) which is the required value. Then the equation can be expressed as

\[ nRT = FP_{s_1} \times V_f + FP_{s_1} \times V_s \]  

(6)

Step 7: As shown in figure 5, repeat step 4. The pressure of the VS1 is recorded as \( FP_{s_2} \) and the pressure of the PA1 is recorded as \( FP_{s_2} \). Then the equation can be expressed as

\[ nRT = FP_{s_2} \times V_f + FP_{s_2} \times V_s \]  

(7)

Combining (6) and (7), the equation can be expressed as

\[ FP_{d_1} \times V_f + FP_{s_1} \times V_s = FP_{d_2} \times V_f + FP_{s_2} \times V_s \]  

(8)

The volume of PA1 can be calculated as

\[ V_f = \frac{(FP_{s_1} - FP_{s_2}) \times V_s}{FP_{d_2} - FP_{d_1}} \]  

(9)

Step 8: The solution flow through the P1 can be calculated as

\[ V_{fi} = V_f - V_i \]  

(10)

where \( V_{fi} \) is the volume of the solution flow through the P1. After substitute (5) and (9) into (10), the equation can be expressed in the following compact form

\[ V_{fi} = \left( \frac{FP_{s_1} - FP_{s_2}}{FP_{d_2} - FP_{d_1}} \times \frac{IP_{s_1} - IP_{s_2}}{IP_{d_2} - IP_{d_1}} \right) V_s \]  

(11)
Figure 4. Solution pushed and valve closed. Figure 5. Solution pushed and valve opened.

From Step 1 to Step 8 we call it an SMP-cycle. Adding up all the SMP-cycles, the dialysate flow can be calculated.

3. Deformation preserving algorithm of time-varying flow resistance

Ideally, the VS1 and PA1 chambers are rigid bodies. But actually the volumes of the chambers change when the pressures change in the chambers. According to our research, the following factor has a greater impact on this change:

When the patients move, the liquid level in abdomen which connected to the SMP will change. Therefore, the flow resistance of dialysate is time-varying. This leads to different $V_{fit}$ in different SMP-cycles, so that the volumes of PA1 were different. Therefore, the deformation of the soft plastic membrane is different and produces a different reverse elastic force. This elastic force causes the air pressure in the VS1 and PA1 to be different in each SMP-cycle. It also causes the volume of the VS1 to change. Because of the non-rigid deformation of the VS1, its volume, $V_s$, is not an invariant quantity, which affects the accuracy of dialysate flow calculation.

For counteracting this effect, we designed an algorithm of deformation preserving for time-varying flow resistance to compensate the errors of dialysate flow calculation.

Take the pulling solution stage of one SMP-cycle (Step1 to Step 4) as an example. Due to the pulling stage is short relative to the whole dialysis stage, the velocity of solution and the flow resistance can be considered as two constants in one pulling stage. We listed the following relations as

$$
\begin{align*}
I_{flow} &= V_{full} / S_{line} = \nu_{flow} \times t_{full} \\
P_{pump} &= f_{res} \times \nu_{flow}
\end{align*}
$$

where $V_{full}$ is the volume of the P1 to be filled up with solution, $I_{flow}$ is the pipeline length that the P1’s solution flowed through, $S_{line}$ is the cross-sectional area of pipeline, $\nu_{flow}$ is the velocity of solution, $t_{full}$ is the time required for the P1 to be filled up, $f_{res}$ is the flow resistance, $P_{pump}$ is the power of air pump. After simplify (12), the flow resistance can be expressed as

$$
f_{res} = \frac{P_{pump} \times S_{line} \times t_{full}}{V_{full}}
$$

where $V_{full}$, $P_{pump}$, $S_{line}$ are invariant quantities. So $f_{res}$ is proportional to $t_{full}$. When the flow resistance changes, the $t_{full}$ should be changed accordingly if we expect the P1 to pull the same volume of solution. As a result, the deformation of the soft plastic membrane is the same in each SMP-cycle so that the value of $V_s$ can be constant relatively.

Record the time $t_{full}$ when the resistance is $f_{res}$. For arbitrary flow resistance the relations can be expressed as
\[
\begin{aligned}
    \begin{cases}
        f_{\text{res}} = P_{\text{pump}} \times S_{\text{line}} \times t_{\text{full}} / V_s = P_{\text{pump}} \times S_{\text{line}} \times t_s / V_{\text{full}} \\
        f_{\text{res}} = P_{\text{pump}} \times S_{\text{line}} \times t_{\text{full}} / V_{\text{full}}
    \end{cases}
\end{aligned}
\]

where $f_{\text{res}}$ is an arbitrary flow resistance, $V_s$ is the volume of solution in P1 when the resistance is $f_{\text{res}}$ and the time is $t_{\text{full}}$, $t_s$ is the time that needs to be used when the resistance is $f_{\text{res}}$ and the P1 needs to be filled up. After simplify (14), it can be expressed as

\[
t_s = V_{\text{full}} \times t_{\text{full}} / V_s
\]

where $t_{\text{full}}$ can be measured with clock, $V_{\text{full}}$ and $V_s$ can be calculated by (11). It should be noted that $V_s$ may not be such accurate, but for figuring out $t_s$ is enough after being updated in 1~2 SMP-cycles. Therefore, for the time-varying flow resistance, the above algorithm can be used to preserve the same deformation of the SMP, so that the error of dialysate flow calculation will be compensated.

4. Experiments

Based on the flow accuracy control method proposed in this paper, we developed a principle prototype, as shown in figure 6. The prototype was converted from a JARI-APD-1 cycler which is clinically recognized in China [11]. To validate its feasibility and effectiveness, the JARI-APD-1 cycler before converted was as contrast group. All subjects were tested with the same parameters to analyze and compare their accuracy differences.

Table 1. Flow error comparison of time-varying resistance.

| Cycler   | Test | Display value /mL | Actual value /mL | Error /mL | Error rate /% | Max absolute error /mL | Error rate range /% |
|----------|------|-------------------|------------------|-----------|---------------|-------------------------|---------------------|
| JARI-APD-1 | 1    | 1000              | 1009.1           | -9.1      | -0.902        | 33.6                    | 4.386               |
|          | 2    | 998               | 964.4            | 33.6      | 3.484         | 33.6                    | 4.386               |
|          | 3    | 999               | 978.2            | 20.8      | 2.126         | 20.8                    | 2.126               |
|          | 4    | 998               | 1006.7           | -8.7      | -0.864        | 8.7                     | 0.864               |
|          | 1    | 1000              | 997.3            | 2.7       | 0.271         | 2.7                     | 0.271               |
| Prototype | 2    | 1000              | 996.8            | 3.2       | 0.321         | 3.2                     | 0.321               |
|          | 3    | 997               | 999.9            | -2.9      | -0.290        | 2.9                     | 0.290               |
|          | 4    | 999               | 1000.6           | -1.6      | -0.160        | 1.6                     | 0.160               |

A bag filled with 1500mL dialysate was simulated an patient’s abdomen. We named it the abdominal-bag. The flow drained from the abdominal-bag was recorded by a FD-XS high-accuracy flowmeter, KEYENCE, Japan. To simulate the time-varying flow resistance, the abdominal-bag was placed at different heights during the cycler working.
Based on the SMP’s position of each cycler, we set three heights: high, medium and low. The high position was 20cm higher than the SMP’s position. The medium position was as high as it. The low position was 20cm lower than it. During the draining, the height of the abdominal-bag was changed in cycle of high- medium- low- medium- high. Each height should be held for 30 seconds. When the total flow displayed on the cycler reached about 1000mL, the test was stopped and the actual flow was recorded. We tested each cycler four times. The flow comparison data were shown in table 1.

The max absolute error reflects the accuracy of flow calculation, which is the less, the better. The error rate range reflects the stability of flow calculation, which is the less, the better. It can be seen from the table 1, the max absolute error of the prototype was less than the JARI-APD-1, which was reduced by 90.5%. Besides, the error rate range of the prototype was less than the JARI-APD-1, which was reduced by 86.1%. The improved accuracy of the prototype was up to 99.7%. Obviously, the accuracy of the prototype was better than that of the JARI-APD-1.

5. Conclusion
In this paper, an accurate calculation model (SMP) and a control algorithm were investigated to address the accurate flow calculation problem for pneumatic driven APD cyclers. The SMP model was built and the steps of using the State Equation of Ideal Gas to calculate the flow are proposed. To reduce the flow calculation error, the deformation preserving algorithm of time-varying flow resistance was designed. The comparative experimental results show that the max absolute error and the error rate range are at least reduced by 90.5% and 86.1% respectively by using our method. The improved accuracy of the prototype can be up to 99.7%. This proves that our method can realize an accurate flow calculation and reduce errors obviously and keep accuracy stable effectively.

Acknowledgments
The author would like to acknowledge the National Key Research and Development Program of China [2018YFB1305900] and the National High-tech Research and Development Program of China [2015AA043102] granting for financial support.

References
[1] Oreopoulos DG, Thodis E (2010) The history of peritoneal dialysis: Early years at Toronto Western Hospital. Dial Transplant, 39(8):338–343.
[2] Chaudhry, Rafia I; Golper, Thomas A (2015) Automated cyclers used in peritoneal dialysis: Technical aspects for the clinician. Med Devices: Evid Res, 8:95-102.
[3] Hidetomo Nakamoto (2012) How automated peritoneal dialysis is applied and maintained in Japan. Contrib Nephrol, 177:13-23.
[4] Mujais S, Childers RW (2006) Profiles of automated peritoneal dialysis prescriptions in the US 1997–2003. Kidney Int, 70 Suppl 103:S84-90.
[5] Alfonso Bunch, Vesga JI, Camargo DO, et al (2019) Remote automated peritoneal dialysis management in Colombia. Kidney Int Rep, 4(6):873-876.
[6] Bieber SD, Burkart J, Golper TA, et al (2014) Comparative outcomes between continuous ambulatory and automated peritoneal dialysis: A narrative review. Am J Kidney Dis, 63(6):1027-1037.
[7] Jose A, Diaz-Buxo (2001) Evolution of continuous flow peritoneal dialysis and the current state of the art. Seminars in Dialysis, 14(5):373-377.
[8] Dell'Aquila R, Rodighiero MP, Spanò E, et al (2007) Advances in the technology of automated, tidal, and continuous flow peritoneal dialysis. Periton Dialysis Int, 27 Suppl 2:S130-137.
[9] Giuliani A, Crepaldi C, Manani SM, et al (2019) Evolution of Automated Peritoneal Dialysis Machines. Contrib Nephrol, 197:9-16.
[10] Ronco C, Amerling R (2006) Continuous flow peritoneal dialysis: Current state-of-the-art and obstacles to further development. Contrib Nephrol, 150:310-320.
[11] Zhao HP, Li SM, Xing CY, et al (2017) The effectiveness and safety of Jerry automated peritoneal dialysis machine for maintenance peritoneal dialysis patients: A multicenter, randomized, and two phase crossover trial. Chin J Blood Purif, 16(3):148-153.