Ultra-filtration Measurement Using CT Imaging Technology

Junfeng Lu 1, Wenqiang Lu 2

1 Technical Institute of Physics & Chemistry, Chinese Academy of Sciences, No.2 Beiyitiao Street, Zhongguancun, Haidian District, Beijing, China, 100190
2 Graduate University of Chinese Academy of Sciences, No.19A Yuquan Road, Shijingshan District, Beijing, China, 100049

junfenglu@mail.ipc.ac.cn

Abstract. As a functional unit in the hemodialysis process, dialyzer captured quite a few medical research interests since 1980s. In the design of dialyzer or in the ongoing hemodialysis process, to estimate the ultra-filtration amount of a dialyzer, the sideway loss of the running blood flow through hollow fibers or filtration channels should be measured. This further leads to the measurement of the blood flow inside the dialyzer. For this measurement, a non-invasive method is highly desired because of the high-dense bundled hollow fibers or packed channels inside the dialyzer. As non-invasive measurement tools, CT (Computed Tomography) technologies were widely used for tissue, bone, and cancerous clinical analyses etc… Thus, in this paper, a CT system is adopted to predict the blood flow inside a hollow fiber dialyzer. In view of symmetric property of the hollow fiber dialyzer, the largest cutting plane that parallels to the cylindrical dialyzer was analyzed by the CT system dynamically. And then, a non-invasive image analysis method used to predict the ultra-filtration amount is proposed.

Keywords. Ultra-filtration measurement, hemodialysis, CT imaging technology

1. INTRODUCTION
On failure of a biological kidney, the patient must be treated by hemodialysis therapy to evacuate metabolic wastes inside his body. The key functional unit in the process of hemodialysis is dialyzer. A cylindrical device shown in Fig. 1 describes an anatomic map of a hollow fiber dialyzer. This device
simulates the physiological functions of a biological kidney. Inside it, a bundle of hollow fibers dousing in dialysate solution perform the functions of kidney nephrons. As blood passing through these fibers, extra water and metabolic wastes such as urea and creatinine carried by plasma are filtered to the outside of the fibers due to the pre-setting of positive transmembrane pressure gradient between dialysate site and blood site. And then, the filtered wastes are removed by dialysate solution running in reverse direction to the blood. Because of its near perfect functionality, these sorts of devices are also called “artificial kidney”. In recent years, due to the warm-up market in artificial biological devices, researchers have gradually joined in the projects of artificial organs. Artificial kidney stills captures big eye-balls in medical research field. And majority of research works were deployed in the design of high efficient more humanlike dialysis devices.

In the analysis of blood flow, dialysate flow or ultra-filtration flow inside the dialyzer, non-invasive measurement technologies are extremely useful because the intrusion of tiny flow measurement pins into a hollow fiber dialyzer is nearly impossible due to high-dense bundled fibers inside the dialyzer. Although Dr. Liao (2005) designed a method to make this measurement, this method is still in contact with blood and could not measure the ongoing blood during hemo-dialysis therapy. Non-invasive or intact measurement is a topic for years interested and studied by thousands of talented researchers. And it is found spreading use especially in medical research, clinical study, biology experimentation, and so on. In today’s medical centers, CT, MRI, ultra-sound, or X-ray machines are diagnostic useful for physicians to make their judgment on patient disease. In view of these modern technologies, a choice of either MRI (Lu, 2005; Poh et al., 2003; Poh, 2003) or CT technology lights up a new way to analyze the flow behaviour inside the dialyzer.

In this paper, we present an image analysis method trying to measure ongoing ultra-filtration flow rate inside a hollow fiber dialyzer using a CT imaging system.

2. METHOD
The idea for the measurement of ultra-filtration flow rate of a hollow fiber dialyzer is based on an observation of the burst of pumped blood flow inside the dialyzer. As shown in Fig. 2, assuming that at time \( t = T_0 + \Delta t \), the frontier of the burst blood flow inside the dialyzer reaches \( Y_i \) and the average flow rate is \( u_i \); after another time interval \( \Delta t \) it reaches \( Y_{i+1} \) with an average flow rate of \( u_{i+1} \), then the blood flow rate of \( u_i \) can be determined by the following equation:

\[
  u_i = \frac{Y_i - Y_{i-1}}{\Delta t}, \quad i > 0
\]

Fig. 2 The bursting blood flow
Holding this equation, the side-way ultra-filtration flow \( v \) could be indirectly measured by the following equation:

\[
v_i = \frac{\left( u_i - u_{i-1} \right) N \pi R^2}{2 N \pi R \left( Y_i - Y_{i-1} \right)}, \quad i > 0
\]

(2)

where \( N \) is the bundle number (number of hollow fibers inside a dialyzer) of a hollow fiber dialyzer, \( R \) is the radius of a hollow fiber. One can further simplify equation (2) as follows:

\[
v_i = \frac{\left( u_i - u_{i-1} \right) R}{2 \left( Y_i - Y_{i-1} \right)}, \quad i > 0
\]

(3)

substitute \( u_i \) by equation (1), one can get:

\[
v_i = \frac{\left( Y_i - 2 Y_{i-1} + Y_{i+1} \right) R}{2 \left( Y_i - Y_{i-1} \right) \Delta t}, \quad i > 0
\]

(4)

With the above equation, one can find that, to measure the ultra-filtration rate of the dialyzer, the only thing left is to find the frontier or \( "Y_i" \) series of the pumped blood flow inside the dialyzer.

The experimental setup for this measurement is shown in Fig. 3. The CT system is used as a camera to capture bursting blood flow pumped by a peristaltic pumping system. And the largest cutting plane that parallels to the cylindrical dialyzer is analyzed.

![Fig. 3 Experimental setup](image)

We capture flow image series between each pumping burst cycle. The time interval between each successive image in the series is set to be \( \Delta t \). And this value is determined by the following equation:

\[
\Delta t = \frac{T}{N}
\]

(5)

where \( T \) is the pumping cycle of the pump and \( N \) is the number of images in the image series.

Fig. 4 shows the captured CT image series \((N=9)\). In the collected images, the dialyzer is fixed on the table by an arm supporter. However, only from these images, one could not specify the blood flow frontier inside the dialyzer. Thus, the image series in Fig. 4 needs more delicate work to rip-off the useless background data. Notice that the background noises as well as support facilities for the
dialyzer inside a captured CT image are inert to time, thus to remove these useless data, the histogram of the CT image is mostly helpful (Fig. 5).

Fig. 4 The raw CT image data captured in a time interval $\Delta t$.

As shown in Fig. 5, by employing multiple-threshold segmentation method (Gonzalez et al., 2003), three thresholds: 50, 108, and 190 (Due to the stability of the background data, these thresholds could be used for all those nine images in Fig. 4) are set to segment out four pattern areas (see Fig. 6) inside the CT image. Among these four patterns, only the area where the dialyzer locates is interested to us because we need to analyze the blood flow inside this area. We further assume the pixel set locking the dialyzer area as $I_{D}$, as well the background area as $I_{B}$. Then the following morphological mechanism could determine the correct enclosing area $I_{o}$ of the dialyzer:
where $\bullet$ is the morphological “closing” operation with structuring element $E$, $\cap$ is the morphological “and” operation, $!$ is the morphological “not” operation, as well, $\circ$ is the morphological “opening” operation. In the realization shown in Fig. 7, a circular structuring element $E$ with a radius of 9 is chosen. In this figure, an enclosing solid structure is locked precisely where the dialyzer should be.

After the deletion of background noises and useless support patterns, next thing left to us is to pick out blood flow data inside the area determined by $I_D$. To do this, before the blood started to burst, a standard static pattern image is recorded by the CT machine as a baseline comparator. We name it as an image pixel set: $I_C$. Let’s further define the image series as: $I_i$ ($i=1,2,\ldots,9$). Thus the following equation will help us to pick out useful data for blood flow inside the dialyzer:

$$I_{blood\_flow} = I_i \cap I_D - I_C \cap I_D$$

Substituting set images in Fig. 4 into equation (7), we get blood flow data as shown in Fig. 8.

At here, the data of blood flow still blurs one’s vision. The layout boundary of the flow frontier cannot be specified even we can perceive a flying pattern (enclosed by a square in Fig. 8) in the image.
series. Moreover this flying pattern is compressed at the outlet area of the dialyzer due to the relatively lower volume flow rate.

To project the frontiers of the bursting blood, a fast numerical interpolation method is desirable. Before we can move forward to interpolate the flow frontier, the frontier boundary points must be picked out. As shown in Fig. 9, we chose image No.1 as an example to clarify the process. Let’s further define the set of these points as:

\[ S = \{(x_i, y_i), i = 1, 2, 3, \ldots, N\} \]  

where \((x_i, y_i)\) is the screen coordinate and is in terms of pixel.

![Fig. 8 Blood flow after ripping-off background noise](image)

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![Fig. 9 Frontier points of image No.1](image)

Fig. 9 Frontier points of image No.1

We assume that the layout boundary of the flow frontier is shaped as parabolic profile and can be described by the following equation:

\[ y = Ax^2 + Bx + C \]  

(9)
To interpolate the layout boundary, a least square parabola method (Mathews et al., 2004) is adopted in this paper. Thus, with those frontier points \((x_i, y_i)\) ever recorded in Fig. 8, the values of \(A, B\) and \(C\) can be exactly determined by the following equations:

\[
A \sum_{k=1}^{N} x_i^2 + B \sum_{k=1}^{N} x_i + C = \sum_{k=1}^{N} y_i x_i^2
\]  
(10)

\[
A \sum_{k=1}^{N} x_i^2 + B \sum_{k=1}^{N} x_i + C = \sum_{k=1}^{N} y_i x_i
\]  
(11)

\[
A \sum_{k=1}^{N} x_i^2 + B \sum_{k=1}^{N} x_i + C = \sum_{k=1}^{N} y_i
\]  
(12)

3. RESULTS & DISCUSSION

Table 1 lists the parabolic interpolation results interpreted by the values of \(A, B\) and \(C\).

Table 1. The values of \(A, B\), and \(C\)

| No. | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \(A_i\) | -12.8 | -13.7 | -14.0 | -13.6 | -12.8 | -13.2 | -17.7 | -18.1 | -22.5 |
| \(B_i\) | 22.6 | 23.9 | 24.5 | 23.9 | 22.5 | 23.3 | 31.0 | 31.8 | 39.5 |
| \(C_i\) | 6.3413 | 6.4178 | 6.6683 | 7.1911 | 7.9829 | 8.6937 | 8.6953 | 9.5109 | 9.5658 |

Fig. 10 shows the normalized interpolation results for the frontier layout boundaries of the 9-image series. To determine the values of “\(Y_i\)” once defined in equation (1), one needs to further carry out a mean value for the frontier layout boundary. This is fulfilled by:

\[
Y_i = \frac{\int_{x_i}^{x_{i+1/2}} y_i(x)dx}{\Delta x}
\]  
\(i = 1, 2, 3, ..., 9\)

\[
= \frac{1}{\Delta x} \int_{x_i}^{x_{i+1/2}} (A x^2 + B x + C_i)dx
\]  
(13)

Fig. 10 Normalized frontier layout boundary of blood flow

Table 2 lists the results of \(Y_i\) series.

Table 2. Normalized \(Y_i\) series

| No. | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \(Y_i\) | 0.5004 | 0.5299 | 0.5648 | 0.6059 | 0.6537 | 0.7071 | 0.7626 | 0.8193 | 0.8772 |

Substituting this \(Y_i\) series into equation (4), we finally get the normalized ultra-filtration rate as shown in Fig. 11. From this figure, one can find that the ultra-filtration on the run from dialyzer inlet to dialyzer outlet is generally decreased. An ideal shape of the ultra-filtration rate should follow the
consine rule if the blood flow was going through a thin porous channel (Lu et al., 2008). The curve of the results shown in Fig. 11 also nearly follows this rule. Since in the experiment, the blood flow recorded by the CT system reflects a mass flow bundled by thousands of tiny flows that are detoured inside the hollow fibers (Fig. 12), and the burst begins at the in-let area of the dialyzer, thus, ultra-filtration mainly happens at the first 1/3 area of the dialyzer.

4. CONCLUSION
The image processing method used in this paper predicted the ultra-filtration amount for a hollow fiber dialyzer, and also knocked another door for the non-invasive flow analysis inside a dialyzer. Even the work needs further delicate corrections (for example, in the experiment, a more sensitive high resolution imaging system with a smaller time interval to record image data could produce better resolution flow images), the results in this paper still generally proves the analytical work deduced by Dr. Lu (2008).

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