Development of patient-specific 1D-0D simulation based on MRI and SPECT data

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1. Introduction

The Circle of Willis (CoW) works as the main center of the cerebrovascular system to supply blood flow to each part of the brain. Blood flow disorders in the CoW will significantly affect the human health. As one of the leading causes of these disorders, the chronic stenosis disease has been investigated for decades [1–4]. One challenge is to understand the hemodynamic effects of the stenosis surgeries.

Although anatomical information such as vessel radius, vessel length, aneurysm size and stenosis ratio can be obtained from noninvasive imaging techniques, it is still difficult to measure the hemodynamic information directly. In particular, the limited resolution achievable with currently available medical imaging techniques poses great difficulty in accurately measuring the hemodynamic information of the cerebrovascular system.

The numerical method combined with the medical imaging data is considered to be a promising way for investigating the hemodynamics of blood flow in the CoW. We have been developing a 1D-0D model to represent the entire cardiovascular system [5, 6]. In our 1D-0D model, the large arteries are assumed to be straight tapered segments represented by the 1D model, the remaining parts of the cardiovascular system such as the heart, capillaries and veins are represented by the 0D model.

The 1D-0D model for the entire cardiovascular system has been investigated widely [7–11]. However, most of them focused on the investigation of general phenomenon of blood flow in the cardiovascular system. In this research, we proposed a method by combining the 1D-0D model with medical imaging data to investigate the hemodynamics of...
blood flow in the CoW for an individual patient. The vessel radius and length measured by MRI are assigned as the arterial geometry parameter for 1D model. The SPECT data are used as the reference to adjust the peripheral cerebral resistance which is represented by 0D model. The proposed method was applied to two patients, the simulation results were then compared with PC-MRI measurement data to evaluate the method.

2. Methods

As illustrated in Fig. 1, the 83 large arteries of the cardiovascular system are represented by the 1D model in this research. The peripheral arteries, capillaries, veins and heart are constructed using the 0D model. The 1D model and 0D model of CoW are connected to one another as shown in Fig. 2. The 1D-0D model thus completes a closed-loop cardiovascular system. The vessel radius and vessel length of the CoW are measured from the MRI data. They are assigned as the geometry parameters for the 1D model. The SPECT data at the efferent arteries (PCAs, MCAs and ACAs) are used to adjust the peripheral resistances of the CoW.

2.1 1D model

The blood flow in the large arteries is assumed to be axisymmetric laminar flow. The governing equations derived from conservation of mass and momentum, are applied to a straight deformable tube:

\[ \frac{\partial A}{\partial t} + \frac{\partial Q}{\partial z} = 0, \quad (1) \]

\[ \frac{\partial Q}{\partial t} + \frac{\partial}{\partial z} \left( \frac{Q^2}{A} \right) + A \frac{\partial P}{\partial z} + K_R \frac{Q}{A} = 0. \quad (2) \]

where \( z \) is the axial coordinate along the vessel, and \( A, Q \) and \( P \) represent the cross-sectional area, flow rate and pressure, respectively. Blood is assumed to be a Newtonian fluid with a constant density \( \rho = 1.06 \text{ g·cm}^{-3} \) and a kinematic viscosity \( v = 4.43 \text{ s}^{-1} \text{cm}^2 \). And \( K_R \) is a resistance parameter related to the viscosity of blood, which is taken as \( 8\pi v \) at the fixed heart rate of 60 bpm in our simulations [13].

The relationship between the pressure \( P \) and area \( A \) is given by: [9]

\[ P - P_0 = \frac{Eh_0}{r_0(1-\sigma^2)} \left( \frac{A}{A_0} - 1 \right). \quad (3) \]

where \( A_0, h_0 \) and \( P_0 \) represent the cross-sectional area, wall thickness and pressure at the reference state, respectively. And \( E \) is the Young’s modulus, \( r_0 \) is the radius corresponding to \( A_0 \), the Poisson ratio is set as \( \sigma = 0.5 \).

2.2 0D model

The 0D model consists of electric circuit series with resistance, capacitance, and inductance. The governing equations are described based on the electrical circuit.

![Fig. 1 Arterial tree composed of 83 vessels described by the 1D model and peripheral cerebral arteries described by the 0D model. (The number in parentheses denotes the arterial segment number.)](image)
analogies as follows:

\[ C \frac{dP_i}{dt} = Q_1 - Q_2, \]  \hfill (4)

\[ L \frac{dQ_1}{dt} + P_1 + RQ_2 = P_i. \]  \hfill (5)

where \( R, C, \) and \( L \) represent resistances, compliance of the vessels, and inductance of the blood, respectively. \( P_1 \) represents the upstream pressure and \( Q_1 \) represents the inflow; \( P_2 \) and \( Q_2 \) are the downstream pressure and outflow, respectively.

### 2.3 Medical imaging data

**MRI**

In our research, the arterial geometry of the CoW were measured with 3D time-of-flight (3D TOF) MRI on a 1.5 Tesla MRI system (MAGNETOM Avanto, Siemens, Munich, Germany), with a field of view (FOV) of 200 mm, repetition time/echo time (Tr/Te) = 28/6 msec, and image resolution = 0.5 × 0.5 × 0.8 mm. The vessel radius and the vessel length were measured using in-house program V-Modeler [12]. These measurements were prescribed as the geometry parameters for the 1D model.

**SPECT**

SPECT is a readily available nuclear medicine technique which is originally applied to qualitatively assess the physiologic function of the brain. After injecting the \(^{123}\text{I}\)-N-isopropyl-p-iodoamphetamine (\(^{123}\text{I}\)-IMP) into the blood, the rotating gamma camera can capture the gamma rays emitted by \(^{123}\text{I}\)-IMP. The image obtained reflects the perfusion map of the brain.

Recently, a new approach has been proposed by Yamada et al. [14] to quantitatively calculate the flow rate in the cerebrovascular system using the SPECT data. In our research, the measured flow rates in the efferent arteries of the CoW were used as the reference data for the adjustment of the peripheral cerebral resistance. In this research, the SPECT measurement was performed with a Siemens E-Cam rotating gamma camera (Siemens, Munich, Germany). The resolution was 64×64 matrix, 9-mm full-width at half-maximum.

**PC-MRI**

The flow rates in the afferent arteries were measured with PC-MRI based on the same system with MRI measurement (slice thickness = 3 mm, pixel size = 256 × 192, FOV = 140 mm, Tr/Te = 24/5 msec, flip angle = 15°). The PC-MRI data was compared with the simulation results to evaluate our method.

### 2.4 Peripheral resistance adjustment

In the present method, the peripheral resistance of each efferent artery of the CoW was adjusted to match the calculated flow rate \( \overline{\Omega} \), which is the average value of one cardiac cycle, with the corresponding reference flow rate \( \overline{\Omega}_{\text{SPECT},i} \) from the SPECT data using the following:

\[ R_{i Q}^{n+1} = R_i^n \left[ 1 - \alpha \cdot \frac{\overline{Q}_{\text{SPECT},i} - \overline{Q}_i^n}{\overline{Q}_{\text{SPECT},i}} \right], i = 58, 61, 63, 65, 67, 70. \]  \hfill (6)

where \( i \) denotes the efferent arterial segment number. \( R_{i Q}^{n+1} \) and \( R_i^n \) are peripheral resistances calculated at the \( n + 1 \)th and the \( n \)th cycle, respectively. \( \overline{Q}_i \) denotes the calculated average flow rate of the \( i \) artery at the \( n \)th cardiac cycle. The parameter \( \alpha = 0.9 \) is a relaxation coefficient. The peripheral cerebral resistance was determined when the difference between \( \overline{Q}_i \) and \( \overline{Q}_{\text{SPECT},i} \) was smaller than a threshold value \( \epsilon \). In this research, all calculations were performed for 40 cardiac cycles to ensure the difference between \( \overline{Q}_i \) and \( \overline{Q}_{\text{SPECT},i} \) was less than 0.1%.

### 2.5 Patient selection

We applied our method to two patients who had received...
stenosis surgeries. The patient in Case1 was 70 years old with North American Symptomatic Carotid Endarterectomy Trial (NASCET) 73% stenosis at Lt.ICA, and was treated by carotid artery stenting (CAS). The patient in Case2 was 82 years old with NASCET 60% stenosis at Rt.ICA and was treated by carotid endarterectomy (CEA). Note that Case2 has hypoplasia in the CoW with no Lt.PCoA (69) and PCA1 (57). The vessel radius and length of the CoW after the surgeries are measured using MRI as shown in Table 1. The extracted vascular geometrical parameters of the CoW were used for 1D simulation, while the geometries of other arteries in the cardiovascular system were based on data from the literature [7, 8, 10, 11, 18–20]. The physiological parameters such as the resistance and compliance of the blood vessels were collected from the literature [7, 8, 19–22]. The literature data of vessel geometry and peripheral resistance are summarized in Table 1.

The SPECT data and PC-MRI data after the surgeries are summarized in Tables 2 and 3. The systolic/diastolic blood pressure of two patients are 107/70 and 151/89 mmHg respectively.

### Table 1 Patient-specific vessel geometry based on MRI data in two cases, and literature data of vessel geometry and peripheral resistance.

| Arterial Segment | i | l [mm] (Lit/Case1/Case2) | r_p [mm] (Lit/Case1/Case2) | r_d [mm] (Lit/Case1/Case2) | R_i [mmHg·s·ml⁻¹] |
|------------------|---|-------------------------|---------------------------|---------------------------|------------------|
| Lt.ICA           | 40| 176.0*                  | 2.5*                      | 2.00/1.65/1.94            |                  |
| Rt.ICA           | 47| 176.0*                  | 2.5*                      | 2.00/1.91/1.88            |                  |
| BA               | 56| 29.0/21.0/23.0          | 1.62/1.89/1.93            | 1.62/1.78/1.64            |                  |
| PCA 1            | 57| 5.0/8.0/NA              | 1.07/1.56/NA              | 1.07/1.52/NA              |                  |
| RT.PCA           | 58| 86.0/20.1/22.5          | 1.05/1.41/1.10            | 1.05/1.24/1.04            | 70.25            |
| RT.PCoA          | 59| 15.0/19.4/15.0          | 0.73/0.46/1.19            | 0.73/0.46/1.11            |                  |
| ICA 1            | 60| 5.0/8.5/7.1             | 2.00/1.87/1.95            | 2.00/1.79/1.46            |                  |
| RT.MCA           | 61| 119.0/9.1/21.5          | 1.43/1.78/1.63            | 1.43/1.66/1.44            | 37.85            |
| ACA 1            | 62| 12.0/14.7/18.6          | 1.17/1.38/1.10            | 1.17/1.36/1.06            |                  |
| RT.ACA           | 63| 103.0/51.7/46.0         | 1.20/1.17/1.13            | 1.20/1.15/0.93            | 53.76            |
| ACA 2            | 64| 5.0/7.6/7.2             | 0.74/1.19/0.91            | 0.74/1.19/0.91            |                  |
| Lt.ACA           | 65| 103.0/57.5/54.2         | 1.20/1.40/1.52            | 1.20/0.96/1.18            | 53.76            |
| ACA 2            | 66| 12.0/16.5/19.8          | 1.17/1.18/1.22            | 1.17/1.18/1.08            |                  |
| Lt.MCA           | 67| 119.0/12.8/28.6         | 1.43/1.63/1.53            | 1.43/1.54/1.43            | 37.85            |
| ICA 2            | 68| 5.0/7.1/2.6             | 2.00/1.77/1.94            | 2.00/1.65/1.94            |                  |
| Lt.PCoA          | 69| 15.0/17.2/NA            | 0.73/0.57/NA              | 0.73/0.57/NA              |                  |
| Lt.PCA           | 70| 86.0/20.7/26.5          | 1.05/1.53/1.36            | 1.05/1.27/0.89            | 70.25            |
| PCA 2            | 71| 5.0/8.3/8.5             | 1.07/1.80/1.36            | 1.07/1.61/1.36            |                  |

“Lit” represents the literature data of vessel geometry; “*”: Only literature data are available; “NA”: Not applicable; Here, i denotes the arterial segment number, l denotes the arterial segment length, r_p and r_d denote the proximal and distal radius, respectively. R_i represents the literature data of peripheral resistance.

### Table 2 Measurement of flow rates in the efferent arteries using SPECT.

| Arterial Segment | \( Q_{SPECT,i} \) [ml/min] | Lt.PCA (70) | Lt.MCA (67) | Lt.ACA (65) | Rt.PCA (58) | Rt.MCA (61) | Rt.ACA (63) | Total |
|------------------|-----------------------------|------------|------------|------------|------------|------------|------------|-------|
| Case1            | 53.0                        | 124.9      | 62.9       | 56.3       | 130.5      | 63.4       | 491.0      |
| Case2            | 37.1                        | 85.4       | 43.4       | 37.2       | 76.9       | 40.6       | 320.6      |

The calculated flow distributions at the afferent arteries were compared with the PC-MRI data as shown in Fig. 3. The differences between the simulation results and the PC-MRI data at BA, Lt.ICA and Rt.ICA for Case1 were 5.5%, 6.0% and 0.6% respectively, while those for Case2 were 13.2%, 5.7% and 7.5% respectively. In proposed method, the SPECT data was used as the reference flow rates at the efferent arteries. Thus, the flow distributions in the efferent arteries were determined by the SPECT data.
Using the patient-specific measurement data of arterial geometry and the SPECT data, the individual difference of the blood flow in the CoW can be predicted with our 1D-0D. Fig. 3(a) showed that, the flow distribution in Rt.ICA was about 40%, while that in Lt.ICA was less than 30% in Case1. This imbalance of flow distribution was caused by the different vessel geometry of the bilateral ICAs. As shown in Table 1, the literature data indicates symmetry in vessel geometry between the left and the right sides of the CoW. Our simulation took into account the patient-specific vessel geometry which showed obvious difference between the left and the right sides of the CoW. Furthermore, the discrepancy in the peripheral resistance due to literature data was corrected to minimize differences between the resulting flow rate and the SPECT data. Therefore, the simulation results showed the corresponding imbalance of flow distribution between the bilateral ICAs with PC-MRI measurement data.

The considerable difference between simulation results and the PC-MRI data in Case2 was likely due to the hypoplasia without Lt.PCoA (69) and PCA1 (57). If there is a hypoplasia in the CoW, the collateral flow may happen not only in the main but also in the secondary cerebral collateral networks, furthermore angiogenesis may also happen in the posterior part to maintain the blood flow supplied to the PCA region [15–17]. The CoW which constitutes the main cerebral collateral network was constructed in our 1D model as shown in Fig. 1. The secondary networks such as tectal plexus and leptomeningeal collaterals were not considered in our model. Also, the possible angiogenesis, associated with the occlusion of a cerebral artery, was not modelled. Due to missing multiple arteries in the CoW in Case2, the secondary networks and angiogenesis may play an important role in regulation of the blood flow in the CoW. The relatively large discrepancy between simulation results and the PC-MRI data in Case2 was resulted from the lack of consideration of these effects in the present 1D-0D model.

The average pressure during one cardiac cycle at the afferent and efferent arteries are depicted in Fig. 4. Since the pressure drop caused by stenosis in ICAs has been treated by surgeries, the pressure in the three afferent arteries exhibited similar values in both cases (Fig. 4a). Since the systolic/diastolic pressure in Case1 was lower than that in Case2, the calculated pressure at the afferent and efferent arteries in Case1 was lower than that in Case2.

![Fig. 3](image1.png)

**Fig. 3** Comparison of flow distributions among the afferent arteries of CoW between the simulation results and the PC-MRI measurements. (a) Case1; (b) Case2.

![Fig. 4](image2.png)

**Fig. 4** Simulation result of pressure in each artery of the CoW. (a) Afferent arteries; (b) Efferent arteries.

| $Q_{PC\text{-}MRI,i}^{\text{ml/min}}$ | BA (56) | Lt.ICA (40) | Rt.ICA (47) | Total |
|-------------------------------|---------|-------------|-------------|-------|
| Case 1                        | 187.0   | 191.3       | 269.9       | 648.2 |
| Case 2                        | 118.7   | 180.4       | 179.5       | 478.6 |

The table above shows the measurement of flow rates in the afferent arteries using PC-MRI.
The peripheral cerebral resistance was adjusted to match the calculated flow rates at the efferent arteries with the SPECT data. Since the flow rate at each efferent artery in Case1 was higher than that in Case2, and the systolic/diastolic pressure in Case1 was lower than that in Case2, the adjusted peripheral resistance at each efferent artery was lower in Case1 than that in Case2. Since the pressure did not change much for the efferent arteries as shown in Fig. 4, the adjusted peripheral cerebral resistance at each efferent artery was inversely proportional to the flow rate in both cases as shown in Fig. 5a and 5b.

Since the SPECT data was originally used to obtain the perfusion map of the brain, utilization of the SPECT data is effective in determining the flow distribution in the CoW, but may have a limit in determining the flow rate accurately. For example, the total cerebral blood flow calculated by the SPECT data in Case1/2 were 491.0/320.6 ml/min, while those calculated by the PC-MRI data were 648.2/478.6 ml/min. As our previous research had proved, the flow distribution in the afferent arteries of the CoW were mainly affected by the vessel geometry and the flow ratios in the efferent arteries [23]. In order to validate our method, the calculated flow distribution results were compared with the PC-MRI data in this research. If the flow rate in each artery of the CoW is the subject of interest, the reference data for the total cerebral blood flow is necessary for the patient-specific 1D-0D simulation.

4. Conclusions

In this research, we developed a method to calculate the flow distribution in the CoW for an individual by using the 1D-0D model combined with the medical imaging data. The measured vessel radius and length from the MRI data was prescribed as the geometrical parameters for the 1D simulation. The SPECT data was used to adjust the peripheral resistance at the efferent arteries of the CoW. The method was applied to two patients after the stenosis surgeries. And the simulation results were validated by comparing with the PC-MRI data at the afferent arteries of the CoW.

Our method can capture the individual difference of blood flow in the CoW among the patients. The simulation showed the pressure was similar at each efferent artery of the CoW. As a result, the adjusted peripheral resistance at the efferent arteries were inversely proportional to the SPECT data.

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