Optimization of Maturation of Radio-Cephalic Arteriovenous Fistula Using a Model Relating Energy Loss Rate and Vascular Geometric Parameters

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ABSTRACT

The main reason for the early failure of radio-cephalic arteriovenous fistula (RCAVF) is non-maturity, which means that the blood flow rate in the fistula cannot increase to the expected value for dialysis. From a mechanical perspective, the vascular resistance at the artificially designed anastomosis causes an energy loss that affects blood flow rate growth and leads to early failure. This research studied how to maximize the RCAVF maturity and primary patency by controlling the energy loss rate. We theoretically analyzed and derived a model that evaluates the energy loss rate E_{avf} in RCAVF as a function of its blood vessel geometric parameters (GPs) for given flow rates. There was an aggregate of five controllable GPs in RCAVF: radial artery diameter (D_{rs}), cephalic vein diameter (D_{cv}), blood vessel distance between artery and vein (h), anastomotic diameter (D_a), and anastomotic angle (θ). Through this analysis, it was found that E_{avf} was inversely proportional to D_{ra} , D_{cv} , D_{a} , and θ , whereas proportional to h. Therefore, we recommended surgeons choose the vessels with large diameters, close distance, and increase the diameter and angle of the anastomosis to decrease the early failure of RCAVF. Simultaneously, we could explain the results of many clinical empiricisms with our formula. We found that increasing D_{cr} and θ was more significant in reducing E_{avt} than increasing D_{ra} and D_{a} . Based on our model, we could define two critical energy loss rates (CEL_a, CEL_b) to help surgeons evaluate the blood vessels and choose the ideal range of θ , and help them design the preoperative RCAVF plan for each patient to increase the maturity and the primary patency of RCAVF.

1. INTRODUCTION

Patients with end-stage renal disease (ESRD) need to undergo hemodialysis (HD) to survive. The arteriovenous fistula is the gold standard for vascular access for hemodialysis, and it is the access recommended by the NFKDOQI [1]. Among all possible AVFs, distal RCAVF is recommended as the first choice of native AVFs. However, due to its small flow capability and thin vessels, the venous outflow after the operation cannot reach the expected blood flow. It will lead to the non-maturation of RCAVF and causes a higher early failure rate. Therefore, the choice of radial artery (RA) and cephalic vein (CV) and the design of the anastomosis play an essential role in the postoperative maturity rate of RCAVF.

We proposed in this study a model to optimize the design of the RCAVF. This new complete model using the interrelation between the different GPs brought scientific probes about the hemodynamic of RCAVF. Our research was inspired by Murray's law [2]. The geometric structure of human blood vessels has evolved according to natural biological selection. The structure of blood vessels follows the principle of minimum energy loss. AVF is an artificial connection of blood vessels. When the energy loss generated by the designed vascular circuit is small, the blood flow is easier to establish so that venous blood flow can reach the target value more easily and quickly, which facilitates the maturation of the AVF.

The research review [3] summarized previous studies and recommended surgeons to choose D_{ra} and D_{cv} equal or greater than 2 mm, and avoid vessels less than or equal to 1.5 mm to ensure the maturity of RCAVF. References [4-6] pointed out that the RCAVF maturity is closely related to D_{ra} and D_{cv} . References [7-11] are based on numerical simulations of different RCAVF shapes to enforce that θ has an impact on the hemodynamic distribution in a fistula by observing the wall shear stress. However, these previous works do not offer theoretical explanations, and literature about the hemodynamic conditions in a recent AVF remains poor. Analyses are often carried out to impact variables separately without considering at least their cross-correlated influences or the interaction with other geometric factors such as h and D_{a} . Actually, surgeons apply some guidelines and have some surgical habits, but with very few scientific probes, and the AVF creation varies from center to center. Our research has considered a set of five a priori inter-connected geometric variables in RCAVF through the control of different GPs to improve recommendations for the creation of RCAVF.

2. METHODS

2.1. Theoretical Analysis

Before the RCAVF creation, surgeons measured and analyzed the quality of the patient vessels through duplex ultrasound and selected the a priori most appropriate AVF according to the D_{ra} and D_{cv} based on their clinical experiences. During the operation, surgeons release the vein over a certain distance to bring the vein to the artery, then cut the vein (CV) obliquely following an angle θ and cut along the axial direction of the artery (RA) a length D_a as shown in **Figure 1(a)**. Then RA and CV will be connected to form the RCAVF vascular access, as depicted in **Figure 1(b)**. The blood flow in the proximal artery (PA) enters the fistula through the heel of the anastomosis with a flow rate Q_h equivalent to that of the normal radial artery (22 mL/min). The blood flow in the distal artery (DA) enters the fistula through the toe of the anastomosis at a flow rate Q_b with the same order of magnitude as that of the wrist (5 mL/min). Q_h and Q_t were calculated by multiplying the average flow velocity in the blood vessel by the cross-section of the vessel [12-14].

 E_{avf} in the RCAVF included energy lost due to vessel bending (E_b) and friction (E_f) in CV, as well as the dissipation of energy due to change in the direction of blood flow (E_d) at the anastomosis. In this research, the blood was laminar flow, and the following assumptions were used:



Figure 1. Radio-cephalic arteriovenous fistula (RCAVF) schematic diagram and geometric parameters (GPs).

- Blood is an incompressible Newtonian fluid ($\rho = 1060 \text{ kg/m}^3$, $\mu = 0.0035 \text{ Pa} \cdot \text{s}$) flowing in a rigid horizontal blood vessel;
- The potential energy and the heat transfer are negligible;
- The energy loss due to metabolism is negligible.

2.1.1. Energy Loss Rate in Bending Cephalic Vein

The energy loss rate along a bending CV segment (Figure 2) consists of E_b and E_f . We assumed that this segment is a concentric bending vessel with a constant diameter D_{cv} . In [15], Idelchik defined E_b as:

$$E_b = \zeta_M \cdot \frac{\rho Q_{cv}^3}{2S_{cv}^2},\tag{1}$$

where ζ_M is the minor loss coefficient of the bending vessel, it can be defined as:

$$\zeta_M = A_1 B_1 C_1 \,. \tag{2}$$

 A_1 , B_1 , and C_1 are defined by:

$$\begin{cases}
A_1 = 0.9 \sin \theta & \text{when } \theta \leq 90^\circ \\
B_1 = 0.21 \left[\frac{D_{cv}}{R_0} \right]^i, R_0 = \frac{h - D_{ra}/2}{1 - \cos \theta} \\
C_1 = 1
\end{cases}$$
(3)

 R_0 is the radius of curvature of the bending segment. When the ratio of D_{cv} to R_0 is less than 1, *i* is equal to 2.5; otherwise, *i* is equal to 0.5. Finally, from Equations (1) to (3), the energy loss rate of the CV segment due to bending could be summarized as:

$$E_b = 0.189 \sin \theta \left[\frac{D_{cv} \left(1 - \cos \theta \right)}{h - D_{ra}/2} \right]^l \frac{\rho Q_{cv}^3}{2S_{cv}^2}.$$
(4)

When blood transports in vessels, the frictional forces will cause pressure loss, thereby consuming energy. The energy loss rate due to friction [2] in this segment could be expressed as:



Figure 2. Blood flow in bending cephalic vein.

$$E_{f} = \frac{128\mu(h - D_{ra}/2)\theta Q_{cv}^{2}}{\pi D_{cv}^{4}(1 - \cos\theta)}.$$
(5)

2.1.2. Energy Loss rate at Anastomosis

Placement of the fistula allows the blood flow in RA to bypass the distal resistance generated by the capillary in the fingers and return to the heart through the anastomosis. For that reason, Q_t flow rate direction of the distal artery changes and flows into the vein together with Q_h (Figure 3). Q_{con} represents the total blood flow rate at the confluence, which equals Q_{cv} . The resulting energy loss rate at anastomosis could be expressed as:

$$E_{a} = E_{t} + E_{h} = \left(K_{t} + K_{h}\right) \frac{\rho U_{con}^{2}}{2} Q_{con} = \left(K_{t} + K_{h}\right) \frac{\rho Q_{cv}^{3}}{2S_{con}^{2}}.$$
(6)

The minor loss coefficients at toe and heel are K_t and K_h [16] defined by:

$$K_t = 2\left(1 - q_t\right)^2 \frac{1}{\varphi_t} \cos\left(\frac{\pi + 3\theta}{4}\right) - 2q_t^2 \frac{1}{\varphi_t} \cos\left(\frac{3\theta}{4}\right) + q_t^2 \frac{1}{\varphi_t} + 1$$
(7)

$$K_{h} = 2q_{h}^{2} \frac{1}{\varphi_{h}} \cos\left(\frac{\pi + 3\theta}{4}\right) - 2\left(1 - q_{h}\right)^{2} \frac{1}{\varphi_{h}} \cos\left(\frac{3\theta}{4}\right) + q_{h}^{2} \frac{1}{\varphi_{h}} + 1, \qquad (8)$$

where q_t and q_h are the ratios of the toe and the heel volume flow rate to the common flow rate. φ_t and φ_h are the ratios of the toe and the heel cross-sectional areas to the common one. They can be expressed as:

$$\begin{cases} q_t = \frac{Q_t}{Q_{con}}, \\ q_h = \frac{Q_h}{Q_{con}}, \end{cases} \begin{cases} \varphi_t = \frac{S_t}{S_{con}}, \\ \varphi_h = \frac{S_h}{S_{con}}. \end{cases}$$
(9)

Next, we introduced the calculation of the cross-sectional area of the total blood flow at the confluence (S_{con}), as shown in **Figure 4**. In the anastomosis operation, surgeons cut CV obliquely to obtain an elliptical cross-section $S_{a_{cv}}$ (the light blue ellipse in **Figure 4**), the major axis is $A_{a_{cv}}$, and the minor axis is $B_{a_{cv}}$:

$$A_{a_cv} = \frac{D_{cv}}{\sin\theta}, \quad B_{a_cv} = D_{cv}.$$
 (10)

Then RA is cut along the axial direction and opened along the radial direction of the blood vessel to obtain an elliptical anastomosis S_a with a major axis A_a and a minor axis B_a (A_a is equal to the anastomotic diameter D_a , and B_a is equal to RA radius R_{ra}). In order to suture CV and RA, S_{a-cv} needs to be stretched or compressed along the major axis to give it the same shape as S_a (the red ellipse in **Figure 4**). The S_{con} section is perpendicular to the CV axial direction after the CV is stretched or compressed (the black ellipse in



Figure 3. Blood flow at anastomosis.



Figure 4. 3D simplified diagram of the anastomosis operation. Top is the original CV artery before being stretched (middle) to be linked to the RA (bottom).

Figure 4 with the major axis A_{con} and the minor axis B_{con}). S_{cv} in **Figure 4** represents the cross-section of CV, a circular cross-section with a diameter of D_{cv} . **Figure 5** presents the top view and the front view of the blood vessel in the CV stretch segment (the light blue lines in **Figure 5(a)** and **Figure 5(c)** represent an undeformed vein). We supposed that B_a and B_{con} evolved linearly from D_{cv} , and A_{con} could be calculated from A_a , D_{cv} , and the θ angle of the imposed deformation. After geometric calculations, the expression of A_{con} and B_{con} were:

$$\begin{cases} A_{con} = D_a \sin \theta - \frac{\left(D_a \sin \theta - D_{cv}\right) D_a \cos \theta}{2h + D_a \sin \theta \left(1 - \cos \theta\right)} \\ B_{con} = \frac{D_{ra}}{2} + \frac{\left(2D_{cv} - D_{ra}\right) D_a \cos \theta \left(1 - \cos \theta\right)}{4h\theta} \end{cases}$$
(11)

Therefore, the cross-section of the total blood flow at the S_{con} confluence could be obtained from:

$$S_{con} = \frac{\pi A_{con} B_{con}}{4} \,. \tag{12}$$

2.1.3. Total Energy Loss Rate in RCAVF

From Equations (4), (5), and (5), the total energy loss rate in RCAVF (E_{avt}) was given by the following equation:

$$E_{avf} = E_b + E_f + E_a$$

= 0.189 sin $\theta \sqrt{\frac{D_{cv} (1 - \cos \theta)}{h - D_{ra}/2}} \frac{\rho Q_{cv}^3}{2S_{cv}^2} + \frac{128\mu (h - D_{ra}/2)\theta Q_{cv}^2}{\pi D_{cv}^4 (1 - \cos \theta)} + (K_t + K_h) \frac{\rho Q_{cv}^3}{2S_{con}^2}$ (13)

where K_b , K_h , and S_{con} could be obtained by Equations (7), (8), and (12).



Figure 5. Top view, 3D view, and front view of cephalic vein (CV) after stretching. (a) Top view; (b) 3D view; (c) Front view.

2.2. Model Validation

In order to validate the model, we compared E_{avf} calculated by Equation (13) and E_{avf_num} obtained with Foam-extend 4.0 numerical simulations. To ensure the relevance of the model, the comparison was made for 25 RCAVF 3D shapes created with Catia V5.

In Equation (13), there was a total of 5 GPs (D_{rab} , D_{cv} , h, D_{a} , and θ). We created a standard model (as a reference of fixed values of GPs as shown in **Table 1**), then only changed one GP each time. For a given GP, we selected five values within its range (**Table 1**) and kept the remaining GPs consistent with the standard model. Therefore, we created a total of 25 models. The details of the models are shown in **Table 2**.

In foam-extend 4.0, we used pisoFoam [18] solver to simulate the flow in these geometries with the same initial conditions (flow rate and pressure). After numerical convergence, the pressure at anastomosis inlets (S_b , S_h) and outlet (S_{cv}) (**Figure 6**) could be extracted. They denoted respectively P_b and P_{cv} . According to the law of energy conservation, E_{avf_num} of each model can be calculated by:

$$\frac{\rho}{2}\frac{Q_t^3}{S_t^2} + P_t Q_t + \frac{\rho}{2}\frac{Q_h^3}{S_h^2} + P_h Q_h = \frac{\rho}{2}\frac{Q_{cv}^3}{S_{cv}^2} + P_{cv}Q_{cv} + E_{avf_num} \,.$$
(14)

 Q_t and Q_h are the flow rates at arterial inlets (Table 2). According to mass conservation, Q_{cv} is equal to the sum of Q_t and Q_h .

3. RESULTS AND DISCUSSIONS

3.1. Comparison between Numerical and Analytical Results

We calculated E_{avf} for 25 models using Equation (13) and compared them with E_{avf_num} obtained by numerical simulations. The comparisons were shown in **Figure 7**. The blue dots in **Figure 7** represent the analytical results (E_{avf}), and the red dots represent the numerical results (E_{avf_num}). We could observe that, for each geometric parameter, E_{avf_num} and E_{avf} had the same profile. The relative difference between the two results defined as ($|E_{avf} - E_{avf_num}|/E_{avf}$) was shown in **Table 3** for each case. The relative difference between the two approaches was less important when analyzing the impact of the variation of D_{cv} or h. It varied between 1% and 7% for D_{cv} . For h, it oscillated between 1% and 9%. In the case of D_{ra} and D_{av} the relative difference was greater and reached 12%. In all cases, the difference between the two approaches was



Figure 6. RCAVF simulation model.



Figure 7. Comparison of numerical results and analytical results in 25 models.

Table 1	. The	research	ranges	of 5	GPs.
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GPs	$D_{ra}(m mm)$	$D_{cv}(\mathrm{mm})$	<i>h</i> (mm)	$D_a(m mm)$	heta (°)
Research range	[1, 4]	[1, 4]	[5, 50]	[4, 12]	[10, 90]

Table 2. Parameters of simulation models.

			GPs			
Models	$D_{ra}(\mathrm{mm})$	$D_{cv}(mm)$	<i>h</i> (mm)	D_a (mm)	$ heta(\degree)$	- Initial Condition
Standard Model	3	3	12	6	30	
	2					
	2.5					
Model 1 - 5 $(D_m \text{ change})$	3	3	12	6	30	
	3.5					
	4					_
		2				
		2.5				
$(D_{cv} \text{ change})$	3	3	12	6	30	
		3.5				
		4				_
			4			$Q_t = 5 \text{ mL/min};$
Madal 11 15			8			$Q_h = 22 \text{ mL/min};$
(<i>h</i> change)	3	3	12	6	30	$P_{cv} = 8.7 \text{ mmHg}$
			16	16		(CV outlet pressure [17])
			20			_
				4		
				6		
$(D_a \text{ change})$	3	3	12	8	30	
				10		
				12		_
					30	
Model 21 - 25					45	
$(\theta \text{ change})$	3	3	12	6	60	
-					75	
					90	

Models	1	2	3	4	5	6	7	8	9	10
Relative Difference (%)	8.99	4.97	0.94	8.86	11.38	6.92	2.41	0.94	1.06	2.50
Model	11	12	13	14	15	16	17	18	19	20
Relative Difference (%)	9.03	2.29	0.94	5.71	4.58	8.84	0.94	5.59	8.81	12.64
Models	21	22	23	24	25					
Relative Difference (%)	0.94	7.49	9.80	10.82	11.61					

Table 3. Relative difference between numerical results and analytical results.

minimal for the standard value of the geometric variables. The difference became greater when the geometric variables moved away from the reference values. Whereas for the θ , the difference between the numerical approach and the model tended to increase from 1% to 11% when the angle increased.

These differences could be explained by the simplifications of the geometry of the RCAVF made for this study. Another possible explanation was linked to the assumptions made initially in [16] on which we relied to establish the expression of E_a given by Equation (6). Nevertheless, we could consider that these differences between E_{avf} and E_{num_avf} remain within an acceptable range. Therefore, Equation (13) established here could reasonably be exploited to predict the energy loss rate in RCAVF.

3.2. Relationship between *E*_{AVF} and GPs

We used Matlab2017 to analyze deeper the relationship between E_{avf} and the different GPs. The curves illustrating this relationship are represented in Figures 8-12. For each figure, the evolution of E_{avf} as a function of a GP was illustrated. For each GP, the evolution of the E_{avf} was parametrized by one of the remaining GPs (subfigures a to d). The three remaining GPs were kept constant and equaled to their respective value corresponding to the standard model given in Table 2.

Thus, **Figure 8** shows the relationship between E_{avf} and D_{ra} . In **Figure 8(a)**, we set h, D_a , and θ to the standard constant values and changed D_{cv} . From this figure, we observed that for all the values of D_{cv} , the E_{avf} decreased when the D_{ra} increased. For a fixed value of D_{ra} , the energy loss rate was lower when the D_{cv} increased. The decrease in E_{avf} as a function of D_{ra} was more pronounced for the smaller D_{cv} values. This general tendency to have lower losses as the diameter of the artery or vein increases could be explained by lower blood velocities at constant flow and larger diameters. As a result, the friction decreased.

In **Figure 8(b)**, we set D_{cv} . D_a , and θ to the constant values and changed h. The behavior of E_{avf} versus D_{ra} was the same as in the previous case. The energy loss rate decreased when D_{ra} increased. Here, on the other hand, for a fixed value of D_{ra} , the energy loss was more significant when the distance h increased. This result seemed consistent since the friction loss rate was proportional to the distance traveled by the blood. A greater distance h implied a greater length of the bending vein, so a more significant energy loss rate appeared.

Figure 8(c) portrayed the relationship curve between E_{avf} and D_{ra} when D_{cv} , h, and θ were unchanged, and D_a was changed. Here the behavior was the same as for **Figure 8(a)**. A larger diameter was the source of a more limited energy loss rate.

Figure 8(d) gives the evolution of E_{avf} as a function of D_{ra} and θ when D_{cv} , h, and D_a are unchanged. The decrease in the angle accentuated the decrease in E_{avf} as a function of the diameter.

Without detailing the analysis of all **Figures 8-12**, it was possible to conclude that we had the following general tendencies:

1) E_{avt} was inversely proportional to D_{ra} , D_{cv} , D_a , and θ , and proportional to h. In other words, if surgeons want to improve the maturity rate of RCAVF, we suggested them choose RA and CV with larger diameters and closer distance and make an anastomotic plan with a larger anastomotic diameter and anastomosis angle.



Figure 8. The relationship between energy loss (E_{avt}) and radial artery diameter (D_{ra}) .



Figure 9. The relationship between energy loss (E_{avf}) and cephalic vein diameter (D_{cv}) .



Figure 10. The relationship between energy loss (E_{avt}) and vessel distance (h).



Figure 11. The relationship between energy loss (E_{avt}) and anastomotic diameter (D_a) .



Figure 12. The relationship between energy loss (E_{avf}) and anastomotic angle (θ) .

2) Compared to D_{ra} , D_{cv} had a more significant impact on E_{avf} . Large-diameter CV (D_{cv}) could effectively reduce the energy loss rate in the fistula and increase the maturity rate of RCAVF than large-diameter RA (D_{ra}).

Figure 8 and **Figure 9** show that when D_{ra} changed, the range of variation of E_{avf} was much smaller than the change caused by changing D_{cv} . We could also see that the curves in **Figure 9** were steeper than **Figure 8**. Therefore, we could prove that the maturity rate of RCAVF had a significant correlation with D_{cv} and the correlation with D_{ra} was relatively weak. This result agreed with [19], which summarized a clinical survey carried out on 96 patients who used RCAVF for dialysis. The author concluded that fistula maturation correlated with D_{cv} but there was no correlation with D_{ra} .

3) To increase the maturity rate of RCAVF, the choice of θ was more important than D_a .

By comparing Figure 11 with Figure 12, we could observe that variation of E_{avf} with θ was more significant than D_a . When θ increased, the energy loss rate could be effectively reduced in RCAVF. It could be seen from Figure 9(c) and Figure 11(b) that when D_{cv} changed, the effect of D_a on E_{avf} was almost negligible. It could be seen from Figure 11(d) and Figure 12(d) that only when θ was very small, the D_a had some effect on the energy loss. This phenomenon could be explained. The energy loss at the RCAVF anastomosis is mainly caused by the friction E_f of the venous bending segment. The loss due to friction is called the major loss because it is much larger than the minor loss (E_a and E_b) due to local shape changes. The change of θ will cause the length of the venous bending segment to change and thus change the major loss, while the change of D_a will only cause a slight change in E_a . Therefore, compared with θ , the influence of D_a on E_{avf} is almost negligible.

4) When *h* was large, it was recommended to choose a larger D_{cv} or decrease the distance between the vessels to reduce E_{avf} .

It could be observed from Figure 10(b) and Figure 10(d) that the greater the *h*, the greater the influence of D_{cv} on E_{avf} . Therefore, for some patients with RA and CV on different sides of the arm, the selec-

tion of D_{cv} was particularly important. If the patient's CV (D_{cv}) was too small or the anastomosis design could not be achieved due to the limitation of the muscles or other tissues in the arm, in order to guarantee the maturity at this point, we could decrease the h (for example, releasing part of the CV in the forearm) to reduce the energy loss rate or choose other types of AVF.

3.3. Critical Energy Loss Rate (CEL)

To ensure the maturity and primary patency of RCAVF, the Kidney disease outcomes quality initiative (KDOQI) [1] and the European Society for Vascular Surgery (ESVS) [20] pointed out in the 2019 vascular access clinical guidelines that it was recommended to use an artery and vein with a diameter greater or equal to 2 mm. From a systematic review [3], the author summarized 12 articles (1200 patients in total) and proposed to use CV and RA with a diameter greater than or equal to 2 mm, and not recommended to use CV and RA with a diameter less than 1.5 mm. In [4-6], the authors also had different proposals for the recommended D_{cv} and D_{ra} ranges. All these suggested critical D_{cv} and D_{ra} values could ensure a high RCAVF maturity rate range from 1.5 mm - 2 mm. However, no research has highlighted a precise critical value of D_{cv} and D_{ra} that can guarantee the maturity of RCAVF. Our analysis found that the reason for this phenomenon was that they ignored the impacts of θ . It could be observed from **Figure 12(a)** that when $D_{cv} = 3$ mm, $D_a = 6$ mm, and h = 12 mm, the E_{avf} generated when $D_{ra} = 1$ mm and $\theta = 70^\circ$ is less than and the case when $D_{ra} = 2$ mm and $\theta = 10^\circ$ mm. Consequently, we could explain why there were still mature cases when D_{cv} or D_{ra} was under 1.5 mm. Therefore, to ensure the RCAVF maturity, the choice of θ was also essential while considering the vessel diameters. We proposed a Critical Energy Loss rate (CEL) concept to help surgeons choose the range of θ reasonably while considering patient's specific D_{cv} and D_{ra}

3.3.1. CEL Definition

The vascular resistance generated at the anastomosis makes it difficult to increase the blood flow in RA, which will lead the blood flow in CV difficult to reach the dialysis standard, thus making the non-mature fistula. Critical energy loss rate referred to the maximum allowable energy loss rate in the RCAVF. When the energy loss rate in RCAVF was less than this threshold, the maturity of the fistula could be guaranteed.

To define the CEL, *h* was set according to the distribution of blood vessels on the forearm of each patient. From the result (3.2.c), since D_a had a relatively lesser impact on energy loss compared to θ , we fixed it to a constant value: 6.41 mm [6]. To ensure the maturity of RCAVF to the greatest extent, CEL was defined as the smallest E_{avf} obtained for the critical D_{ra} and D_{cv} and $\theta = 90^{\circ}$.

This value of CEL was calculated for the critical values of D_{ra} and D_{cv} as reported by [3-6]. Thus, for this analysis, D_{ra} and D_{cv} evolved in the range of 1.5 mm to 2 mm. We were able to deduce an interval [*CEL*_a, *CEL*_b] that could be used to find the best geometry guaranteeing the maturity of the fistula. These conditions were summarized in Table 4.

3.3.2. CEL to Help for RCAVF Anastomoses Design

In reality, D_{ra} , D_{cv} , and h are fixed values for each patient. The purpose of the definition of CEL is to help surgeons assess, from a mechanical point of view, the usability of patients' blood vessels. In the case of usable blood vessels, the concept of critical energy loss could help design the best shape anastomosis.

	GPs					
	$D_{ra}(\mathrm{mm})$	$D_{cv}(mm)$	<i>h</i> (mm)	$D_a({ m mm})$	$ heta(\degree)$	
CEL _a	2	2	Clinic data of the notiont	6 41	00	
CEL_b	1.5	1.5	Chine data of the patient	0.41	90	

Table 4. Definition of CEL.

In this analysis, we maintained D_a at a constant value of 10 mm, which corresponded to the value practiced by our hospital partners. D_{ra} , D_{cv} , and h values for each patient could be measured by duplex ultrasound. Therefore, we could get the relation between E_{avf} and θ ($E_{avf}(\theta)$), as shown in Figure 13. The black curves in Figure 13 represent the evolution with θ of the energy loss rate in RCAVF calculated using the reel D_{ra} , D_{cv} , and h of each patient. The red and blue lines present CEL_a and CEL_b , respectively. With CEL_a and CEL_b , we could calculate θ_a and θ_b through the $E_{avf}(\theta)$ curve, which provided a range of critical θ .

We divided the anastomosis design into three possible levels, as shown in **Table 5**. When θ was greater than or equal to θ_a , E_{avf} was less than or equal to CEL_a (the red area in **Figure 13**), this θ range was the most recommended range, and we defined it as the A-level anastomosis design. When θ was between θ_a and θ_b , E_{avf} was between CEL_a and CEL_b (the blue area in **Figure 13**). At this time, θ was classified as B-level. If surgeons choose θ within this range, the performance of the patient's blood vessel wall properties should be evaluated. For patients with low vascular wall elasticity and curved blood vessels, surgeons must combine their own clinical experiences to use θ within this range before surgery. For an anastomosis design with θ smaller than θ_b , E_{avf} was greater than CEL_b (the grey area in **Figure 13**). This type of anastomosis design was not recommended. There was a high chance that it will cause the failure of RCAV maturation.

Not all the blood vessels could get θ_a and θ_b . Through the $E_{avt}(\theta)$ curve in **Figure 13**, the blood vessels used for RCAVF was divided into three types:



Figure 13. The relationship between E_{avf} and θ regarding the critical energy loss.

Table 5.	Recommended	level for	anastomosis	design.
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Recommande Levels	Definition	Comments
С	$CEL_b \leq E_{avf}$	Not recommend
В	$CEL_a < E_{avf} < CEL_b$	Must combine surgeons' clinical experiences
А	$E_{avf} \leq CEL_a$	Recommend

Type I: θ_a and θ_b could be calculated,

Type II: Only θ_b could be calculated,

Type III: Neither of θ_a or θ_b could be calculated.

We recommended that surgeons choose the blood vessel Type I with an A-level anastomosis design to ensure RCVAF maturity and primary patency. For the blood vessel of Type I and Type II with B-level anastomosis design, the surgeons needed to evaluate the patient's vascular performance in advance. For RCAVF with C-level anastomosis, all three types of blood vessels were not recommended.

4. CONCLUSIONS

In most cases, native RCAVF is the preferred VA strongly recommended by clinical practice guidelines [1, 20]. It has the advantages of longer survival patency, fewer complications, and lower risk of infection, making it have lower morbidity and mortality and could reduce the patient's financial burden. Nevertheless, its high early failure rate (46%) [21] is still a big problem now. A recent study [22] proposed that the traditional vein-to-artery configuration could be changed to the artery-to-vein, thereby increasing the maturity rate and primary patency of the native fistula. Our study also concentrated on fistula configuration optimization. It was the first study that proposed to help surgeons design the fistula shapes from the perspective of energy loss, thereby increasing the RCAVF maturity rate.

Through this study, we analyzed the relationships between the energy loss rate in RCAVF and its five associated GPs, and then verified their accuracies with numerical results. It was found that D_a and D_{ra} had much less influence on energy loss than θ and D_{cv} , and the distance between blood vessels *h* also had a non-negligible influence on E_{avf} . For patients who use RCAVF for dialysis, we suggested surgeons choose the vessels with the larger diameters and a small distance while increasing the angle and diameter of the anastomosis to decrease the energy loss.

To help surgeons create a RCAVF plan for patients, we defined two energy loss rate thresholds: CEL_a and CEL_b , and used them to classify blood vessels into three types and anastomotic design into three levels. These could help surgeons access the operability of the patient's blood vessel and select the most appropriate anastomosis angle range for the patient.

This new complete model studied the different GPs. The anastomotic angle seemed to be an important parameter, more than the anastomotic diameter. This result may raise some questions about surgical theories regarding the treatment of AVF complications, such as high flow correction. Depending on the model, reducing D_a to reduce high-flow AVF may not have real meaning. To verify this result, other studies must be conducted on mature AVF using this model.

This model can also be used to design other native AVFs and AVG (arteriovenous graft) shapes. In use, the inlet flow rate and GPs need to be reset, and the minor loss coefficients K_t and K_h in this model need to be changed according to relevant references when blood flow direction at the anastomosis changes.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper.

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