Renal Replacement Therapy

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Relationship between resistance index and recirculation rate in vascular access

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Abstract

Background: The state of vascular access affects the efficiency of hemodialysis. Poor blood flow of vascular access causes recirculation, which reduces treatment efficiency. In the clinical setting, the resistance index (RI) is a commonly used parameter to evaluate the state of vascular access. However, there are few reports investigating the direct relationship between RI and the recirculation rate. In this study, the relationship between RI and the recirculation rate was investigated using computational fluid dynamics analysis.

Methods: We created a three-dimensional model that mimics vascular access in hemodialysis patients. Next, we input various blood flow waveforms (RI 0.00, 0.50, 0.60, 0.80, and 0.94) into the vascular model. Then, two needles were punctured into the blood vessel model. Blood was removed from the vessel by one needle at a rate of 200 ml/min and returned by the other needle at the same speed. The recirculation rate was calculated using the backflow from the blood return needle.

Results: The recirculation rates for the blood flow waveforms of RI 0.00, 0.50, 0.60, 0.80, and 0.94 were 0.00%, 0.29%, 0.44%, 11.6%, and 28.1%, respectively. The recirculation rate was higher for blood flow with higher RI. In addition, more recirculation occurred during the diastolic phase, when blood flow was slow.

Conclusions: When the minimum blood flow was slower than the hemodialysis blood removal speed, both backflow and the recirculation rate increased. Sufficient diastolic blood flow needs to be maintained to suppress recirculation.

Keywords: Recirculation rates, Resistance index, Hemodialysis, Vascular access, CFD analysis

Background

There is a general trend toward a substantially increased number of patients receiving maintenance dialysis worldwide [1]. Vascular access is vitally important in maintenance hemodialysis (HD) because vascular access-related complications are one of the major causes of hospitalization for dialysis patients [2]. Vascular access requires adequate blood flow, long-term patency, and ease of cannulation. There are three main types of vascular access used in maintenance HD, namely arteriovenous fistula (AVF), arteriovenous graft (AVG), and central venous catheter. More than 90% of stable HD patients use AVF as vascular access in Japan [3]. AVF is the preferred access option for all HD patients, as it is associated with a lower risk of mortality and fatal infection compared with AVG or central venous catheter [4].

Adequate HD is important to reduce morbidity risk in maintenance HD patients [5]. Vascular access recirculation is defined as the return of dialyzed blood to the arterial segment of the access bypassing the systemic circulation [6]. The early detection of stenosis by measurement of the recirculation rate or blood flow and early

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intervention reduces access failure and prolongs the useful life of AVF [7]. Doppler ultrasound (US) closely correlates with fistulography in diagnosing stenosis, and the US evaluation of AVFs in HD patients is a simple method to predict the risk of thrombosis and fistula dysfunction [8, 9]. The resistance index (RI) of the brachial artery is a common parameter in the US evaluation of AVFs. The RI after AVF creation can predict primary patency and help plan intervention [2, 10]. Although several reports have described the relationship between blood flow and the recirculation rate [5, 6], the relationship between RI and the recirculation rate has not yet been clarified. Therefore, we investigated the effect of RI on the recirculation rate using computational fluid dynamic (CFD) analysis in vascular access.

Methods

This study used OpenFOAM®, a program for CFD analysis. First, the vascular model to be analyzed by CFD was created using FreeCAD® with reference to the AVF of a dialysis patient. The inner diameter of the vascular model is 5.0 mm, and two needles are stuck at intervals of 5.0 cm in the vascular model; the needle insertion angle is 15 deg.

Table 1 shows the material parameters of the blood to be analyzed. Viscosity is the same as blood with hematocrit 35%. Next, in order to investigate the relationship between RI and the recirculation rate, different flow waveforms of RI were flowed in from the inlet of the vascular model. Then, the outflow and inflow from the two needles were set to 200 ml/min. The RI waveforms examined were 0.00, 0.50, 0.60, 0.80, and 0.94. The verified flow velocity waveform is shown in Fig. 1. The flow rate of the input waveform was unified at 500 ml/min. For the flow velocity of the input waveform, the maximum and minimum velocities were determined with reference to formula 1 so that they would be the RI values to be verified. Next, a curve was drawn so that the velocity component from the maximum velocity to the minimum velocity gradually decreased, and the velocity at each point was readjusted so that the area under the curve was the same for all waveforms. By making the area under the curve the same, all of the flow rates will be the same.

Table 1 Material parameters

Parameters	Value
Density [kg/m^3]	1060
Dynamic viscosity [Pa/s]	$2.8 * 10^{-3}$
Kinematic viscosity [m^2/s]	$2.6 * 10^{-6}$
Reference pressure [Pa]	101,325
Reference temperature [K]	309

Other boundary conditions are shown in Table 2. The waveforms simulated the ejection of one beat per second except for the steady flow. Since blood removal and blood return of the dialysis machine are performed by a roller pump, blood removal and blood return are pulsatile. These pulsatile flows may affect the recirculation rate, but the rotation speed of the roller pump is about 20 rpm and the blood flow is 200 ml/min, which is small compared to the shunt blood flow. Therefore, in this study, in order to simply verify the relationship between RI and recirculation, we considered that the effect of the pulsating flow of the roller pump was small and calculated blood removal and blood return as steady flow.

The vascular model outlet length is 300 mm, which is 60 times the inner diameter, and the outlet pressure is 0 Pa. The calculation interval was 0.1 s, and the calculation was performed for 5.0 s. In addition, pimpleFoam®, an incompressible unsteady diversion solver, was used for the calculation. The calculation of the recirculation rate was based on the report that verified the recirculation rate with a dialysis catheter [11]. As shown in formula 2, the recirculation rate is the ratio of return flow to removal flow. The backflow rate required for the calculation used the flow rate between the two needles using ParaView®, a CFD visualization program.

$$\mathrm{RI} = \frac{\mathrm{Velocity\ (Max)} - \mathrm{Velocity\ (min)}}{\mathrm{Velocity\ (Max)}} \tag{1}$$

$$\text{Recirculation rate [\%]} = \frac{\text{Backflow rate [ml/min]}}{\text{200[ml/min](return flow)}} \times 100 \tag{2}$$

Results

The created vascular access model is shown in Fig. 2. It was designed so that the tip of the needle is in the center of the vessel, and the distance between the two needles is 5.0 cm. Figures 3 and 4 show the flow velocity in the cross section of the vessel model. Blood flow is from left to right in the blood vessel model in the figure, and the part where the flow is fast is shown in red. The part where the flow velocity is slow is shown in yellow and green, and the part that is backflow from right to left is shown in blue. Figure 3 shows a flow velocity diagram of RI 0.00 (steady flow). Since the flow velocity in the model was constant, the flow velocity distribution between the venous needle and the arterial needle was almost constant. Figure 4 shows a flow velocity diagram at RI 0.94. In the systolic phase with maximum flow velocity, there was no backflow from the venous needle to the arterial needle. However, in the diastolic phase when the flow velocity decreased, there was backflow from the venous needle to the arterial needle, and recirculation was observed.

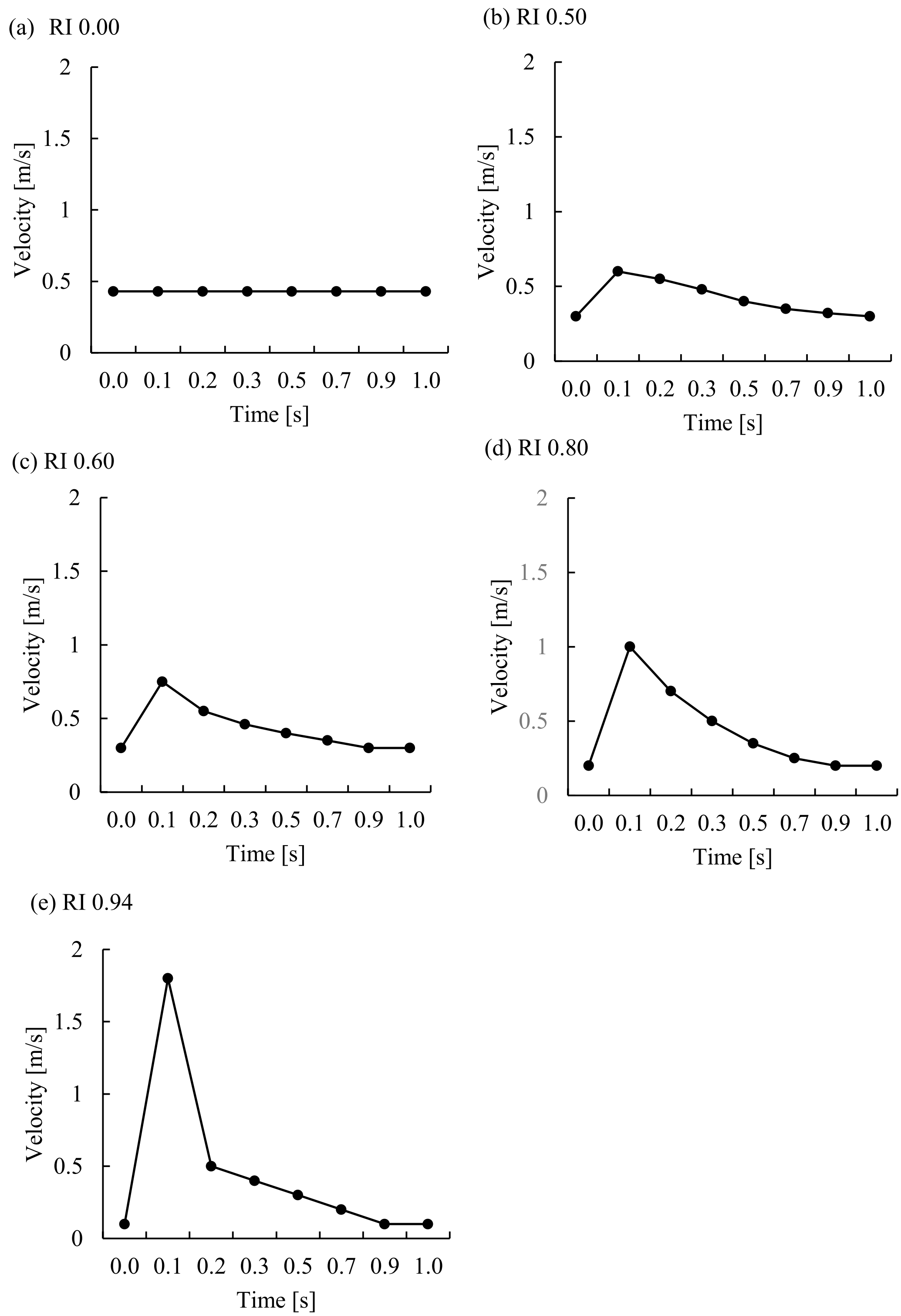

Fig. 1 Input waveform. **a** RI 0.00 (steady flow), **b** RI 0.50, **c** RI 0.60, **d** RI 0.84, **e** RI 0.94. The flow rate is unified to 500 ml/min

Table 2 Boundary conditions

Boundary	Field	Value
Vascular inlet	Velocity	0.1–1.8 [m/s]
	Pressure	Zero gradient
Vascular outlet	Velocity	Zero gradient
	Pressure	0 [Pa]
Blood return needle	Velocity	$3.33 * 10^{-6}$ [m^3/s]
	Pressure	Zero gradient
Blood removal needle	Velocity	$-3.33 * 10^{-6}$ [m^3/s]
	Pressure	Zero gradient
Other walls	Wall (no slip)	–

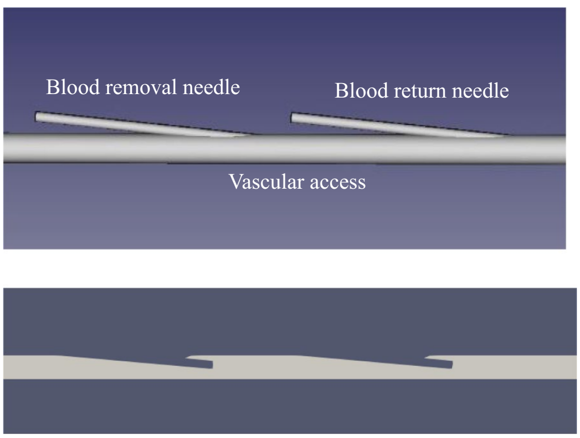

Fig. 2 Vascular access model. The inner diameter of the blood vessel is 5.0 mm and the total length is 50 cm (outlet length: 30 cm). The inner diameter of the needles is 1.7 mm. The distance between the two needles is 5.0 cm

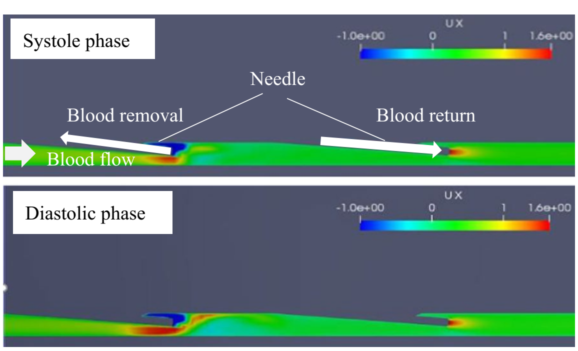

Fig. 3 Velocity distribution map (RI 0.00). Blood flow is from the left side of the figure. The flow velocity distribution did not change significantly over time, and no recirculation was observed

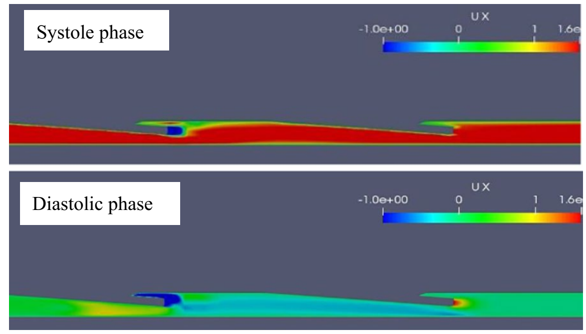

Fig. 4 Velocity distribution map (RI 0.94). Blood flow is from the left side of the figure. The blood flow from left to right is depicted in red. Backflow is depicted in blue. Recirculation was observed during the diastolic phase

Figure 5 shows a flow velocity graph of the cross section at the midpoint between the arterial needle and the venous needles. The graph shows the time change of the flow velocity, and the backflow rate per unit of time is calculated by multiplying the area surrounded by the curved part of under 0 m/s and the horizontal axis by the cross-sectional area of the blood vessel. When the RI was 0.00, steady flow, there was no backflow between the needles, and the recirculation rate was 0.00% (Fig. 5a). When the RI was 0.50, the minimum speed between needles was −0.02 m/s and the recirculation rate was 0.29% (Fig. 5b). A negative velocity between needles means that backflow has occurred from the venous needle to the arterial needle. When the RI was 0.60, the recirculation rate was 0.44% (Fig. 5c). When the RI was 0.80, the minimum speed was −0.13 m/s, the time when the speed became negative was longer, and the recirculation rate was 11.6% (Fig. 5d). In the case of RI 0.94, the minimum speed was −0.24 m/s, the percentage of time when the flow velocity was negative was the maximum, and the recirculation rate was 28.1% (Fig. 5e). Figure 6 shows the relationship between RI and the recirculation rate. The higher RI, the higher recirculation rate. When RI is 0.6 or less, the recirculation rate is almost 0%.

Discussion

In this study, we focused on the relationship between RI and the recirculation rate. These are common parameters that show the blood flow status of vascular access but, to date, there are no reports verifying that RI is directly related to the recirculation rate. Against this background, we created a vascular access model for HD and verified the relationship between RI and the recirculation rate using CFD analysis. CFD is a useful option for the investigation of vascular access [12, 13]. As expected, we showed that recirculation increases as RI increases in actual HD therapy, and that sufficient diastolic blood flow needs to be maintained to suppress recirculation.

Although the recirculation rate was only 0.44% for the blood flow waveform of RI 0.60, the recirculation rate

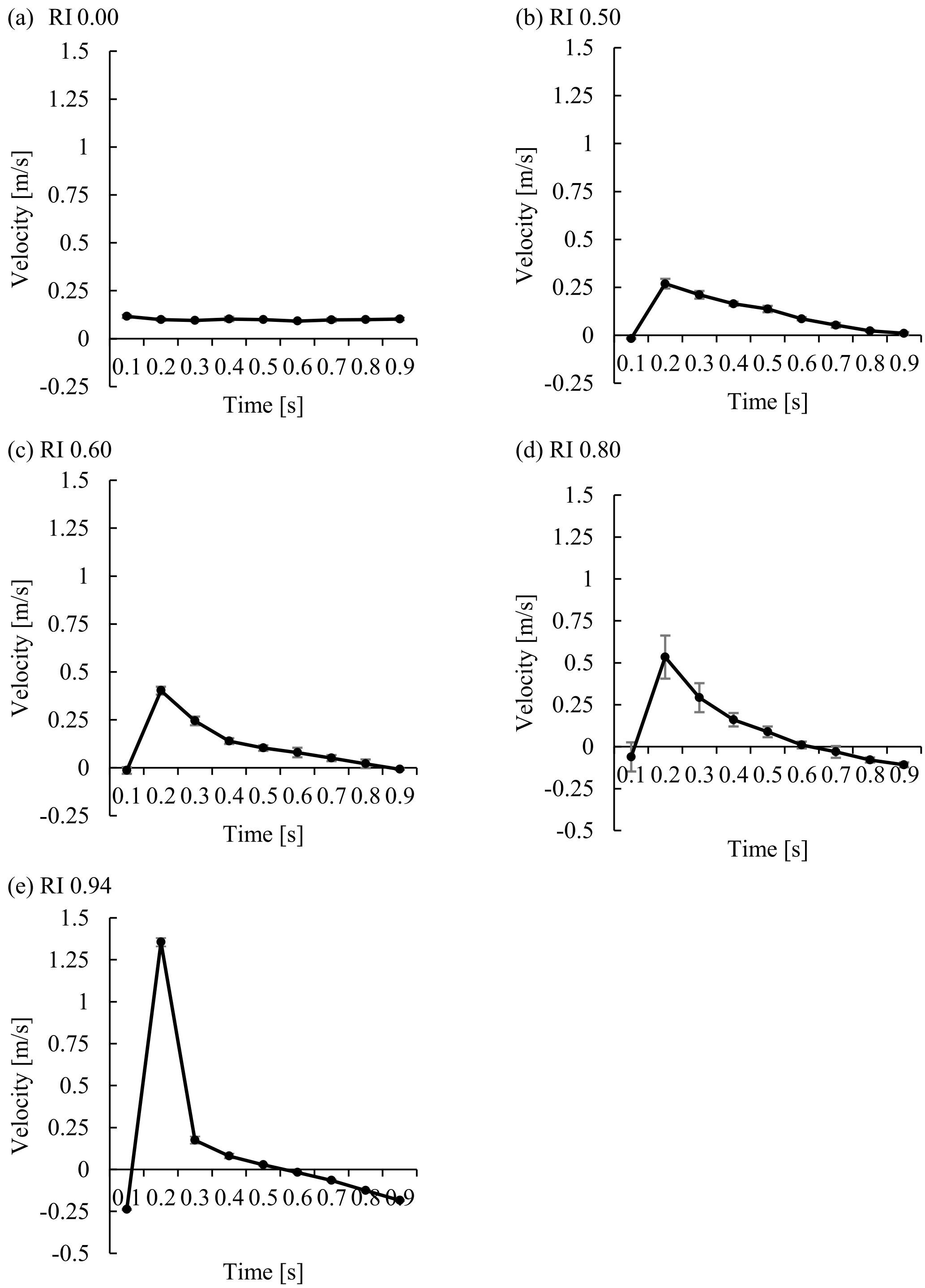

Fig. 5 Output waveform. **a** RI 0.00, **b** RI 0.50, **c** RI 0.60, **d** RI 0.84, **e** RI 0.94. These show the change in flow velocity at the midpoint between blood return and blood removal

for RI 0.80 significantly increased to 11.6%. The Japanese Society for Dialysis Therapy (JSDT) guidelines for vascular access recommend further investigation of vascular access if the recirculation rate is over 5% or RI is over 0.6 [14]. The recirculation rate in each RI of this study is in line with the JSDT guidelines.

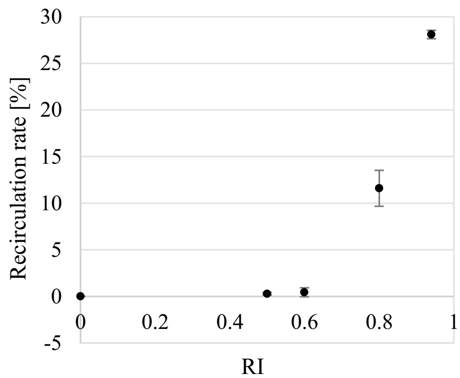

Fig. 6 Recirculation rate

The occurrence of recirculation in HD reduces dialysis efficiency. Fulker et al. reported that turbulence around the needle is involved in causing recirculation. According to their report, turbulence originates from the blood return needle, and the turbulence that can lead to recirculation may be due to anatomical structures such as vascular stenosis rather than the position of the needle in each patient-specific case [15]. Ono et al. stated that it is important to focus on the blood flow waveform pattern rather than just the average shunt blood flow value to explain the shunt dysfunction from the verification using the experimental circuit. In addition, they speculated that recirculation or decreased actual blood removal flow would occur when the diastolic shunt flow falls below the set blood flow [16]. This study revealed that higher recirculation was observed in the diastolic phase, which has slower blood flow. Usually, decreased blood flow in the dialysis circuit occurs when the blood pressure is low, even if there is no stenosis in the AVF. A previous study using catheters also reported that the recirculation rate increased as the intravascular blood flow decreased [17]. We speculated that the reason for this was that when the flow velocity in the vascular model was lower than the blood removal rate, negative pressure was generated around the arterial needle. The negative pressure causes backflow from the venous needle. In addition, a blood flow waveform with a high RI creates a steep peak waveform, and the diastolic blood flow velocity tends to be small. Therefore, we considered that the recirculation rate increases with high RI blood flow with small diastolic blood flow velocity. The RI usually increases with the stenosis of blood vessels, although we believe that, in addition to the increase in RI due to stenosis, the decrease in diastolic blood flow was also associated with the occurrence of recirculation.

A previous study reported that if the access condition is good according to CFD analysis, the risk of recirculation is lowered by moving away from the anastomotic site, even if the needle distance is short [18]. In the case of the model verified here, the distance between the venous needle and the arterial needle was 5.0 cm, and recirculation began to occur when the diastolic blood flow fell below 30 cm/s. Therefore, if the needle spacing is further widened, it can be expected that recirculation will be less likely to occur, even if the flow velocity falls below 30 cm/s. Furthermore, it can be expected that when the blood flow through the vascular access increases and the flow velocity increases, the backflow rate from the venous needle will decrease and the recirculation rate will decrease. Normally, as the blood flow increases, the blood vessel diameter also increases. In other words, it is predicted that when the systemic blood pressure is decreased, well-developed vessels easily engage in recirculation. This needs further analysis in the future.

This study has the following limitations. First, the vascular model in this study has no bifurcation, although the recirculation rate is affected by the degree of branching. Second, we estimated the relationship between RI and the recirculation rate under fixed parameters, such as puncture angle, needle tips, and diameter. A previous study reported that the risk of recirculation increases when the needle angle is shallow and the tip of the needle is close to the roof or bottom of the blood vessel [19]. Third, it is known that actual blood flow is often reduced in cases of shunt dysfunction. In this study, the blood flow was fixed at programmed value, and the vascular diameter was also fixed, so it should be noted that the occurrence of recirculation was reproduced rather than the decrease in the actual blood flow. Although this study has the above limitations, we showed that recirculation increases as RI increases. In addition, we also revealed that sufficient diastolic blood flow needs to be maintained to suppress recirculation. We considered that in the case of a proximal stenosis of the blood return needle, recirculation increases as RI increases, and sufficient diastolic blood flow is needed, similar to this model.

Conclusions

As a result of CFD analysis, even if the blood flow in the AVF used for HD is the same, the recirculation rate may increase when RI is high. In addition, it is necessary to maintain sufficient diastolic blood flow in order to suppress recirculation.

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Author contributions
KU designed the study and conducted experiments. JI, YU, MI, and KN interpreted the results and contributed to discussion. KU and NT wrote the manuscript. TK supervised this study. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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