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Articles

Experimental investigation of tip shape effect on suppression of sticking and recirculation in double lumen catheters

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I. Introduction

The double-lumen catheters (DLCs) used in hemodialysis include both blood removal and blood return routes in a single catheter. Issues associated with the use of DLCs include blood removal failure, thrombus formation, stenosis or occlusion of the indwelling catheter, and infection. Blood removal failure is a particular problem, and severe blood removal failure may make continued treatment infeasible. The main reasons for blood removal failure include: thrombus formed near the DLC tip; sticking of the blood removal holes to the vascular wall; and fibrin sheath formation, when proteins adhere around the catheter and block the holes. One method of dealing with blood removal failure is to connect the DLC in reverse. Although the reverse connection may release the sticking and improve blood removal, the major problem is that it increases the likelihood of recirculation, in which blood that has already been purified by the dialyzer is drawn back into the dialyzer, reducing the efficiency of dialysis. The DLCs currently in clinical use all have various adaptations made by different manufacturers. DLCs with a special tip design in which the blood removal and blood return holes are placed back-to-back have come onto the market in recent years. Under conventional thinking, this design means that the distance between the blood removal and blood return holes, L_{AV}, is zero, and the recirculation rate should therefore increase. The holes are also not shaped as simple circles, but are three-dimensional streamlined ellipses that follow the line of the lateral surface. This special hole shape is believed to help reduce the recirculation rate despite the fact that L_{AV} is zero, but the reason for this has yet to be identified. In this study, the flow in the vicinity of the tips of three different DLCs was visualized, and the inflow pressure distribution within those DLCs was measured, with the aim of ascertaining the reason.

II. Experimental Methods

1. Visualization of the flow in the vicinity of the DLC tip with a high-speed camera

Figure 1 shows the experimental system for

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visualizing the flow in the vicinity of the DLC tip. A colorless, clear vinyl chloride tube with internal diameter of 12-mm was connected as a simulated vessel to one of the horizontal flow route connectors of a T-shaped connector. A similar tube was also connected to the connector running at right angles to the horizontal flow route, and water was pumped through the simulated vessel with a small gear pump to simulate blood at flow rates of 200 ml/min, 400 ml/min, and 700 ml/min. The other horizontal flow route connector was closed with a rubber stopper with a hole in it, and a DLC was inserted through this hole so that the tip was positioned in the center of the tube. In this study, three different types of DLC with the special tip shape were used: a Palindrome Precision (PD-DLC), a Power-Trialysis Slim-Cath (PT-DLC), and a Muhurkar Elite Catheter (MH-DLC). The arterial connection port of the DLC was connected to the arterial blood circuit, and the venous connection port was connected to the venous blood circuit. The arterial and venous blood circuits were connected to each other with a straight connector. Simulated blood was removed from the DLC at a flow rate of 200 ml/min using the roller pump of a dialysis unit. A three-way stopcock was fitted immediately behind the pump segment of the arterial blood circuit, and a syringe pump was attached, from which a mixture of water and tracer particles for use in visualization was injected at a constant flow volume. After the simulated blood had been removed via the DLC arterial holes, the mixture of water and tracer particles was returned to the simulated vessel via the venous holes. A high-speed camera was positioned directly in front of the DLC tip. The tracer particles were ejected from the blood return holes into the simulated vessel, and their movement from there through the simulated vessel was filmed with the high-speed camera. Filming was carried out with a frame rate of 1000 fps and a shutter speed of 1/2000 s.

The PD-DLC and PT-DLC both withdraw blood via two blood removal holes, one at the catheter tip (the tip hole) and one on the side of the catheter (the side hole). To investigate which of these holes has a greater effect on recirculation, flow visualization was conducted, and the recirculation rate was measured when the side hole was blocked with vinyl tape. The blood removal hole of the MH-DLC is called a “side slot” and is streamlined three-dimensionally along the lateral surface, and flow visualization and recirculation rate measurements were performed when half of the central side of this hole was closed with a vinyl tape.

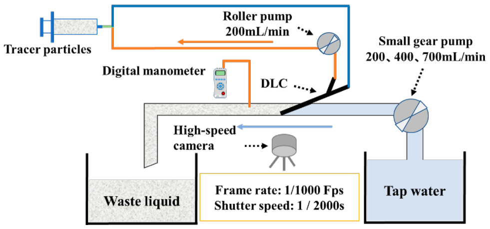

Fig.1 Experimental system for visualizing the flow in the vicinity of the DLC tip

3. Pressure distribution measurements within the DLC using a pressure guidewire

Figure 2 shows the experimental system for measuring the blood removal pressure distribution within the DLC using a pressure guidewire. A T-shaped connector was connected on the downstream side of the simulated vessel, and a tube was connected as a simulated vessel to the connector running at right angles to the horizontal flow route. The other connector of the horizontal flow route was connected to a blood transfusion extension tube. The pressure guidewire was inserted through this extension tube, and the insertion depth was adjusted so that the wire’s pressure sensor was positioned in the center of the DLC blood removal route. The pressure guidewire was then connected to a special monitor, and the blood removal pressure imposed on the blood removal hole at different locations was measured while the wire was withdrawn toward the DLC tip. A dialysis roller pump was used for simulated blood removal at a rate of 200 ml/min and a small gear pump for circulation within the simulated vessels at a flow rate of 700 ml/min. The blood removal pressure measurement positions were set with respect to the DLC tip as the origin (zero).

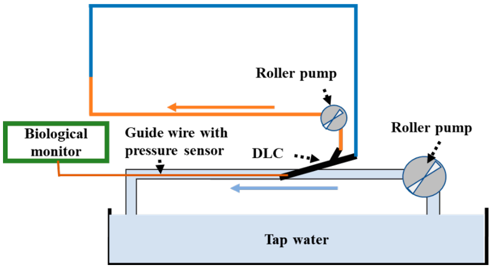

Fig.2 Experimental system for measuring the blood removal pressure distribution within the DLC

III. Results

Figure 3 shows the results of high-speed camera observations of the state of recirculation with different flow rates within the simulated vessels with the PD-DLC, PT-DLC, and MH-DLC. At a flow rate of 200 ml/min, recirculation in which tracer particles ejected from the blood return hole were again sucked into the blood removal hole occurred in all the DLCs. At a flow rate of 400 ml/min, no recirculation was observed with the PT-DLC. However, recirculation in which tracer particles were again sucked into the blood removal hole occurred in the PD-DLC and the MH-DLC. At a flow rate of 700 ml/min, recirculation was only observed with the MH-DLC. ***Figure 4*** shows the results of flow visualization in the vicinity of the DLC tip when the side holes of the PD-DLC and the PT-DLC and half of the central side of the side slot of the MH-DLC were blocked. Recirculation was observed to occur in all three types of DLC at every flow rate. Lower flow rates in the simulated vessels resulted in a greater amount of tracer particles being sucked in.

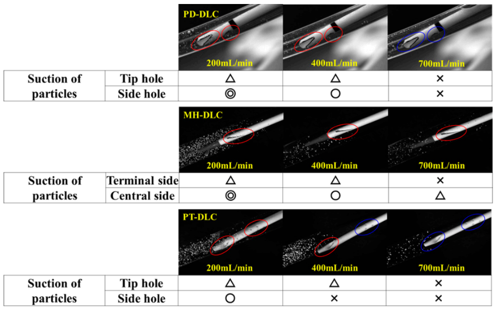

Fig.3 Results of flow visualization in the vicinity of the DLC tip using a high-speed camera

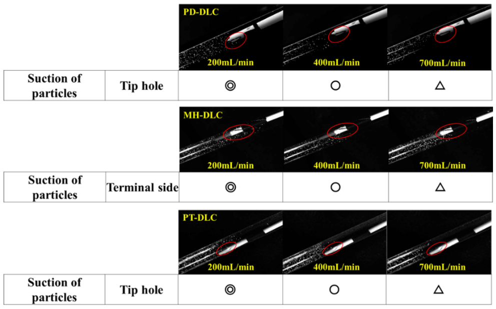

Fig.4 Results of flow visualization in the vicinity of the DLC tip when the side holes were blocked

Figure 5 shows the results of blood removal pressure distribution measurements in the PD-DLC, PT-DLC, and MH-DLC. In all three DLCs,

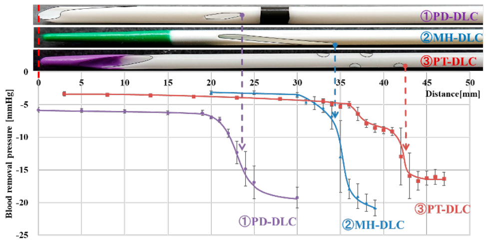

Fig.5 Results of blood removal pressure distribution measurements in DLCs

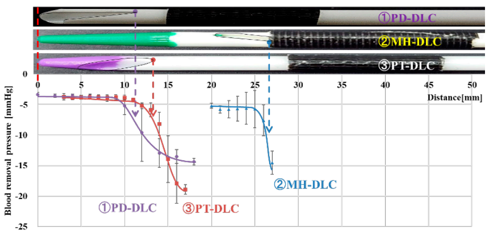

Fig.6 Results of blood removal pressure distribution measurements in DLCs when the side holes were blocked

negative pressure increased rapidly at either the blood removal hole furthest from the DLC tip or at the end of the blood removal hole. ***Figure 6*** shows the results when the side holes of the PD-DLC and the PT-DLC or half of the central side of the side slot of the MH-DLC were blocked. It can also be seen from ***Figure 6*** that negative pressure increased rapidly at the site furthest from the DLC tip.

IV. Discussion

The results of flow visualization in the vicinity of the DLC tip showed greater stagnation and retrograde flow of tracer particles in the PT-DLC and MH-DLC compared with in the PD-DLC. This is considered to be due to the locations of the blood return holes. The PD-DLC and PT-DLC have holes at the tip and on the side of the catheter on the blood return side, and the side hole of the PD-DLC is closer to the tip than that of the PT-DLC. There was almost no tracer particle outflow from the side hole in either DLC, with the tracer particles flowing out of the larger-sized tip hole. However, the opening of the tip hole in the PD-DLC extends from the tip to the side of the DLC, whereas the tip hole of the PT-DLC opens to the side a little way from the DLC tip. This difference in blood return hole structure means that the tracer particles ejected from the blood return hole of the PD-DLC flow linearly downstream, whereas those ejected from the blood return hole of the PT-DLC follow a spiral orbit along the surface of the wall of the vinyl chloride tube. The MH-DLC has only a single blood removal hole that opens on the side of the DLC, and the tracer particles were also seen to follow a spiral orbit along the surface of the wall of the tube, in the same way as from the PT-DLC. This may be why recirculation was observed at a flow rate of 400 ml/min inside the simulated vessels with the PD-DLC, which has back-to-back blood removal and blood return holes, and the MH-DLC, which was more susceptible to tracer particle stagnation. The blood removal and blood return holes of the PT-DLC are separated, which may be the reason why no recirculation was observed with the PT-DLC. When the side holes of the PD-DLC and PT-DLC and the half of the central side of the side slot of the MH-DLC were blocked, the blood removal and blood return holes of all three types of DLC were adjacent to each other, and this may have increased the amount of recirculation.

Turning to the results of blood removal pressure distribution measurements for each DLC, the rapid increase in negative pressure at either the blood removal hole furthest from the DLC tip or at the end of the blood removal hole seen in all three types of DLC may have been caused by the shape and positioning of the blood removal hole. During inflow, the pressure in the dialysis circuit upstream from the roller pump and the DLC is negative. The PD-DLC and PT-DLC have a structure with a larger tip hole and a smaller side hole. This means that negative pressure is easier to maintain at the side hole, which is closer to the negative pressure source and has a smaller area. In contrast, at the tip hole, negative pressure is harder to maintain because of its greater distance from the negative pressure source and its larger area. The results of the experiments visualizing the flow in the vicinity of the DLC tip also confirmed that, when the side hole was open, there was almost no inflow via the larger tip hole, with inflow occurring mainly via the side hole. Similarly, in the MH-DLC, as well as the PD-DLC and PT-DLC, when the side holes were blocked, negative pressure could be maintained at the end of the blood removal hole close to the negative pressure source, but not at the DLC tip. The fact that negative pressure is not generated equally at all the blood removal holes, and, in particular, that negative pressure is not generated at the tip hole, which has a larger area, may be one reason why the incidence of sticking of DLCs to the vascular wall is reduced.

Ⅴ. Conclusion

The characteristics of the blood removal and blood return holes of three types of DLCs with characteristic tip shapes were investigated by visualizing the flow in the vicinity of the DLC tip and measuring the blood removal pressure distribution within the DLC, and factors that reduce the incidence of sticking to the vascular wall and of recirculation were identified. Recently, a uniquely shaped DLC has been proposed that has the lumens with blood removal and blood return holes divided into two and a curved shape that prevents sticking to the vascular wall. As a topic for future research, we intend to carry out similar visualization of the flow in the vicinity of the tip of this DLC and measure the blood removal pressure distribution to ascertain the effects of the unique design.

[Notes]

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