Renal Replacement Therapy

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Suction towards a vessel wall by hemodialysis catheters—the establishment of a new experimental extracorporeal circulation system using pig veins

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Abstract

Background: Hemodialysis catheters are commonly used for vascular access in patients undergoing blood purification therapies. However, the sudden dysfunction of catheters represents a serious problem, and while we know that the major causative factor is suction between the catheter and the vessel wall, it is very difficult to evaluate this in vivo. Therefore, we created a new experimental system to investigate this phenomenon ex vivo, using pig veins, which allowed us to quantitatively analyze the effect of suction.

Methods: We attempted to create a model system for quantitative evaluation using azygos veins from a pig. Four types of catheters were inserted into an extracted pig vein: true circle type 1, true circle type 2, semi-circle type 1, and semi-circle type 2. We then circulated 50% glycerol solution through the vein at a flow rate (Qv) from 100 to 1000 mL/min. Glycerol solution was also circulated within the catheters at a flow rate (Qb) from 100 to 200 mL/min. We measured the frequency of suction towards the vessel wall ten times, under each experimental schedule, at a Qb of both 100 and 200 mL/min. We then measured the pressure between the pre-Qb pump and the blood circuit, when the arterial side opening was positioned approximately in the center of the blood vessel to prevent catheter suction towards the vessel wall.

Results: Suction towards the vessel wall occurred 8/10 times with the true circle type 1 catheter and 10/10 times with the semi-circle type 2 catheter in the arterial pore of the catheter is only one, when Qb and Qv were 100 and 100 mL/min, respectively. Suction towards the vessel wall occurred 3/10 times with the semi-circle type 2 catheter, when Qb and Qv were 100 and 1000 mL/min, respectively. The true circle type 1 catheter showed a minimum pressure of -58.6 ± 0.516 mmHg when Qb and Qv were 100 and 300 mL/min, respectively, while the true circle type 2 catheter showed a minimum pressure of -137 ± 5.96 mmHg when Qb and Qv were 200 and 300 mL/min, respectively.

Conclusions: We successfully established a novel ex vivo evaluation system for catheters using a pig vein which allowed us to recreate the effect of suction from catheters towards a vessel wall in vivo.

Keywords: Hemodialysis catheters, Suction towards the vessel wall, Pig vein, Evaluation system

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Background

Hemodialysis catheters (catheters) are commonly used to obtain adequate vascular access in patients who require blood purification therapies. It is highly preferable to begin treatment promptly after inserting a catheter into the femoral vein or internal jugular vein. Thus, catheters are used frequently in patients with acute kidney injury (AKI) [1]. However, catheters often fail during blood purification therapy, most commonly due to catheter suction towards the vessel wall [2], thrombotic occlusion [3], and the development of a fibrin sheath [4]. These issues represent serious problems because there is no suitable method available at present with which to detect and evaluate these phenomena.

Until now, only highly experienced medical staff can recognize catheter dysfunction by individual perception of manipulation alone. When catheter dysfunction occurs, the circulating blood cannot be sent to a blood purification machine, thus making it very difficult to continue with blood purification therapy. Negative pressure in a blood circuit results in a deterioration in dialysis efficiency. A range of factors can cause catheter dysfunction. In particular, end-hole type catheters for high flow are often associated with catheter suction towards the vessel wall. To the best of our knowledge, there are no reports in the published literature which address the issue of quantitatively analyzing catheter suction towards the vessel wall using an ex vivo model.

In the present study, we describe the development of a novel ex vivo model using pig veins which allows us to quantitatively analyze the effect of suctioning towards the vessel wall.

Methods

We used four different catheters in this study (Fig. 1): true circle type 1 (BARD, USA, Georgia), true circle type 2 (BARD, USA, Georgia), semi-circle type 1 (NIPRO, JPN, Osaka), and semi-circle type 2 (Baxter, JPN, Tokyo). The catheter banding patterns show arterial side opening area. The catheter vertically striped patterns show arterial side sectional area. A schematic of the experimental system is shown in Fig. 2. We attempted to develop a model system using azygos veins from a pig (hereafter referred to as "pig vein"). We extracted 10 pig veins, as a model for the human femoral vein, from a 6-month-old pig weighing 120 kg. We selected pig vein 10 ± 2 mm in diameter and no venous valve, and the pig vein was refrigerated and used within the 7 days. The pig vein was set into 50% glycerol solution. We then inserted the catheters into the pig vein, and 50% glycerol solution was circulated around the vein at a body temperature (36 °C) to act as artificial blood. Flow rate in the pig vein (Qv) was set at 100, 200, 300, 500, and 1000 mL/min, in accordance with an earlier publication in which blood flow was reported to be 100~1000 mL/min within a vein [5]. These conditions simulated blood flow in the lower human circulatory system. Each catheter was separately inserted into the same pig vein. The arterial end hole of the catheter was adjusted so that the tip of the catheter's position could meet the target position. Next, we perforated the arterial two side holes of a true circle type 1 catheter. The diameter of these holes was located symmetrically and the upper end hole was 1 mm in diameter. In other words, the end hole of the catheter was located at the tip and on the arterial side. A blood circuit NV-Y871P (NIKKISO, Tokyo, Japan) was the connected to the catheter and glycerol solution was circulated using a DCS-26 blood purification machine (NIKKISO, Tokyo, Japan). We judged that suction towards the vessel wall occurred when Qb changed to 0 mL/min within 10 s of the Qb pump starting. We measured the frequency of suction towards the vessel wall ten times, for each experimental schedule, at a Qb of both 100 and

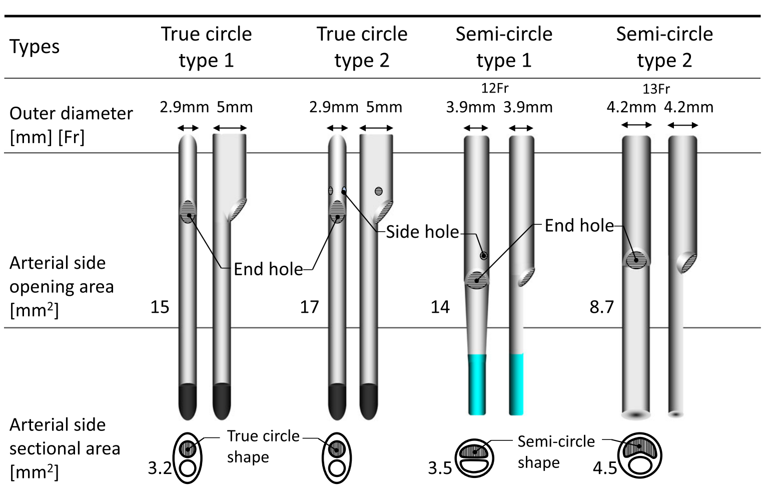

Fig. 1 Specification of the catheters

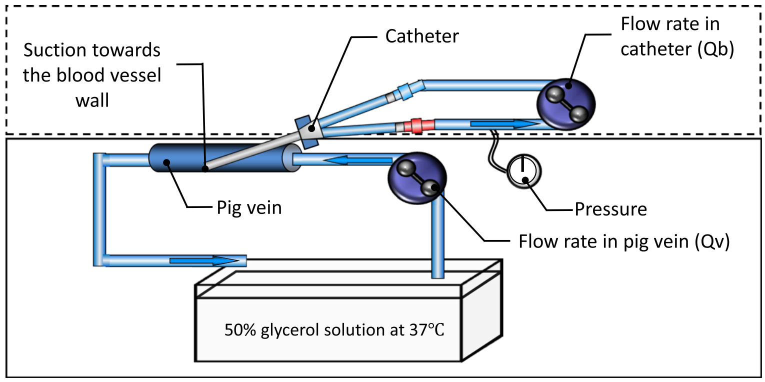

Fig. 2 Experimental system. Solid line shows the circuit of simulated blood vessel and dotted line shows the blood purification circuit

200 mL/min. A Handy Manometer PG-100 N/B (Copal Electronics, Tokyo, Japan) was connected to the blood circuit on the upstream side of the blood pump to measure the difference in negative pressure between the catheter and the pump. Next, we measured the pressure between the pre-Qb pump and the blood circuit when the arterial side opening was positioned in the center of blood vessel to prevent catheter suction towards the vessel wall. The data were analyzed with Scheffé's *F* test and an alpha level of 0.05 using Excel statistics 2012 for windows (Microsoft Corporation, Washington, USA).

Results

The frequency of suctioning towards the vessel wall by the catheters is shown in Fig. 3. Suction towards the vessel wall occurred 8/10 times with the true circle type 1 catheter and 10/10 times with the semi-circle type 2 catheter, when Qb and Qv were 100 and 100 mL/min, respectively (Fig. 3). However, no suction occurred via the side holes of the catheter. Suction towards the vessel wall occurred 10/10 times, with all catheters, when Qb and Qv were 200 and 100 mL/min, respectively (Fig. 3b). Suction towards the vessel wall occurred 2/10 times with the true circle type 1 catheter and 10/10 times with the semi-circle type 2 catheter, when Qb and Qv were 100 and 200 mL/min, respectively (Fig. 3c). Suction towards the vessel wall occurred 10/10 times with all catheters when Qb and Qv were 200 and 100 mL/min, respectively (Fig. 3d), while suction towards the vessel wall occurred 3/10 times with the true circle type 1 catheter, and 10/10 times with the semi-circle type 2 catheter, when Qb and Qv were 100 and 300 mL/min, respectively (Fig. 3e). Suction towards the vessel wall occurred 10/10 times with the true circle type 1 catheter, 2/10 times with the semi-circle type 1 catheter, and 10/10 times with the semi-circle type 2 catheter, when Qb and Qv were 200 and 300 mL/min, respectively (Fig. 3f).

Suction towards the vessel wall occurred 3/10 times with the true circle type 1 catheter, 2/10 times with the semi-circle type 1 catheter, and 5/10 times with the

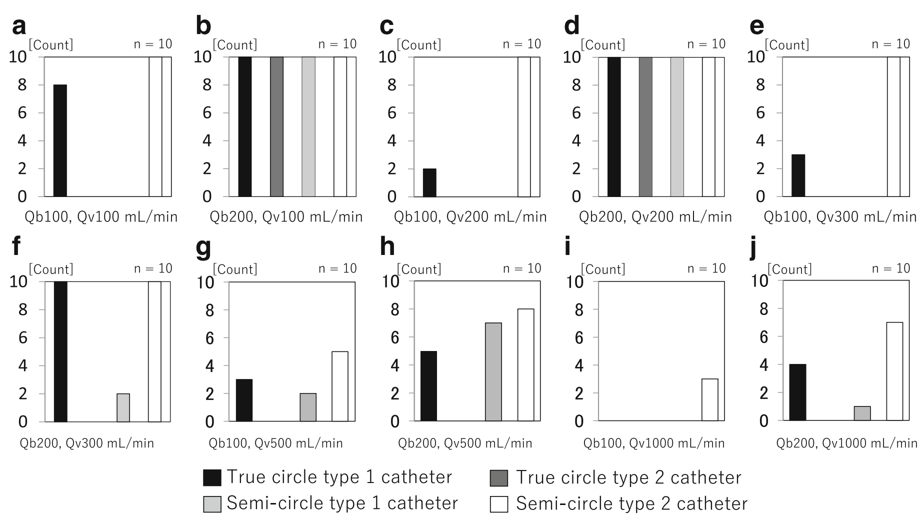

Fig. 3 **a**–**j** Frequency of suctioning towards the vessel wall

semi-circle type 2 catheter, when Qb and Qv were 100 and 500 mL/min, respectively (Fig. 3g). Suction towards the vessel wall occurred 5/10 times with the True circle type 1 catheter, 7/10 times with the semi-circle type 1 catheter, and 8/10 times with the semi-circle type 2 catheter, when Qb and Qv were 200 and 500 mL/min, respectively (Fig. 3h). Suction towards the vessel wall occurred 3/10 times with the semi-circle type 2 catheter, when Qb and Qv were 100 and 1000 mL/min, respectively (Fig. 3i). Finally, suction towards the vessel wall occurred 4/10 times with the true circle type 1 catheter, 1/10 times with the semi-circle type 1 catheter, and 7/10 times with the semi-circle type 2 catheter, when Qb and Qv were 200 and 1000 mL/min, respectively (Fig. 3j).

Arterial pressures are shown in Fig. 4. The true circle type 2 catheter showed a minimum pressure of − 80.3 ± 2.16 mmHg when Qb and Qv were 100 and 100 mL/min, respectively, (Fig. 4a) and a minimum pressure of − 165.3 ± 1.89 mmHg when Qb and Qv were 200 and 100 mL/min, respectively, (Fig. 4b). The true circle type 2 catheter showed a minimum pressure of − 69.5 ± 0.527 mmHg when Qb and Qv were 100 and 200 mL/min, respectively, (Fig. 4c) and a minimum pressure value of − 151 ± 0.919 mmHg when Qb and Qv were 200 and 200 mL/min, respectively (Fig. 4d). The true circle type 1 catheter showed a minimum pressure of − 58.6 ± 0.516 mmHg when Qb and Qv were 100 and 300 mL/min, respectively (Fig. 4e). The true circle type 2 catheter showed a minimum pressure of − 137 ± 5.96 mmHg when Qb and Qv were 200 and 300 mL/min, respectively (Fig. 4f). The true circle type 2 catheter showed a minimum pressure of − 57.4 ± 0. 700 mmHg when Qb and Qv were 100 and 500 mL/min, respectively (Fig. 4g). The true circle type 2 catheter showed a minimum pressure of − 119 ± 0.990 mmHg when Qb and Qv were 200 and 500 mL/min, respectively (Fig. 4h). The true circle type 2 catheter showed a minimum pressure of − 46.6 ± 0.700 mmHg when Qb and Qv were 100 and 1000 mL/min, respectively (Fig. 4i), while the true circle type 2 catheter showed a minimum pressure of − 107 ± 0.630 mmHg when Qb and Qv were 200 and 1000 mL/min, respectively (Fig. 4j).

It is important to note that these catheters differ in their design; the true circle type 1 catheter arterial tip design features one end hole, while the true circle type 2 catheter arterial tip design features one end hole and two side holes. Pressure values were significantly lower for the true circle type 2 catheter than the true circle type 1 catheter ($P < 0.01$, Fig. 4a–j).

Discussion

Several studies have reported that polyvinyl chloride (PVC) and natural rubber tubes can be used as for evaluating catheters in experimental system [6]. However, we believe that these materials significantly influence the results of the evaluation because the Young's modulus is very different in PVC and natural rubber tubes compared to biomaterials. For example, Young's modulus has been reported to be 6.9–29 MPa in PVC, 3000–8000 kPa in natural rubber, but only 40–100 kPa

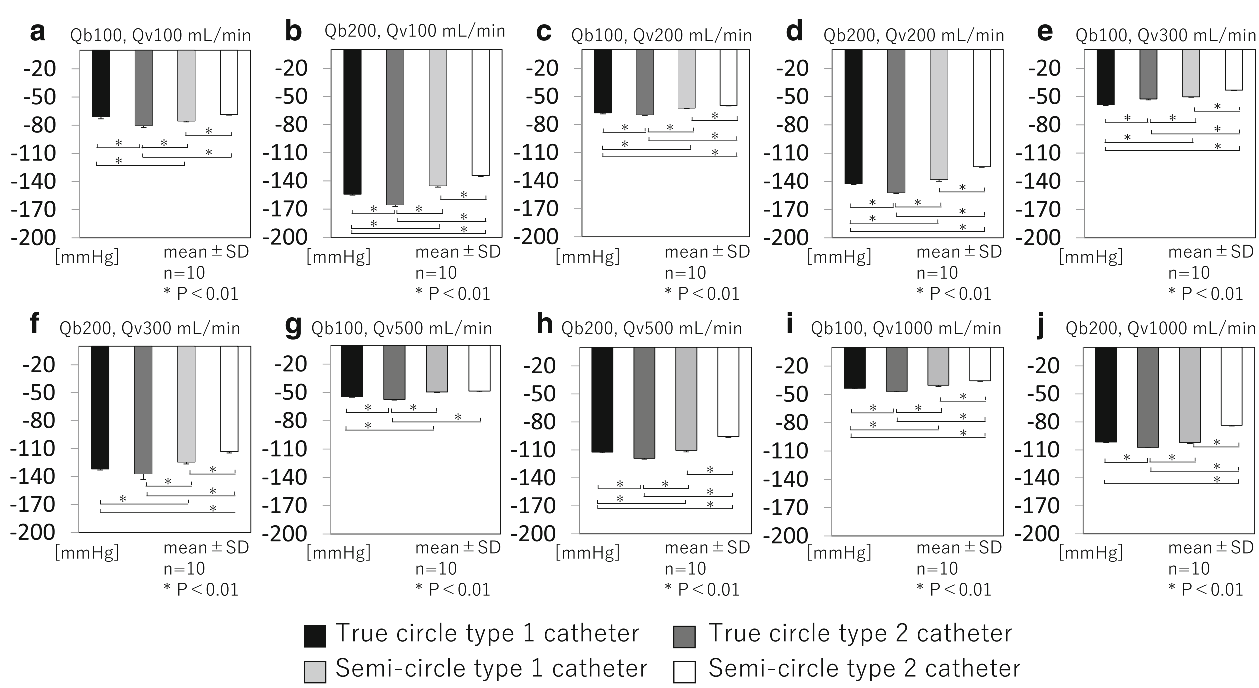

Fig. 4 a–**j** Pre-pump pressure

in the inferior vena cava. It is therefore highly evident that Young's modulus or PVC and natural rubber are low very different from that in the living body. Because of this, in the present study, we chose to use the azygos vein, harvested from a pig, to construct an experimental system for evaluating catheters in conditions which were similar to the living body.

The frequency of suctioning towards the vessel wall

The true circle type 2 catheter showed the lowest frequency of suction towards the vessel wall and was therefore very efficient at preventing suction towards the vessel wall. It is evident that the side holes on this type of catheter can carry blood to a dialyzer, even if the end hole has caused suction towards the vessel wall. In contrast, the true circle type 1 catheter, which does not have side holes, caused suction towards the vessel wall in all of the conditions we examined, although there were variations in the frequency of suction. It is reasonable to consider that the side holes of the True circle type 1 catheter were effective in preventing suction towards the vessel wall. The semi-circle type 1 catheter showed the second lowest frequency of suction towards the vessel wall; this type of catheter possesses not only an end hole but also one side hole of 1-mm diameter, while also featuring a different angle and shape to the opening on the arterial side compared to true circle type 2 catheters. We considered that the true circle type 1 catheter and the semi-circle type 2 catheter caused incidences of suction towards the vessel wall because of their lack of side holes. In addition, we believe that differences in frequency of suctioning towards the vessel wall between the true circle type 1 and semi-circle type 2 catheters were most likely caused by the angle and shape of the opening on the arterial side. The end hole of a catheter with a shallow opening angle can easily cause suction towards the vessel wall; in our case, the semi-circle type 2 catheters have a shallower opening angle than that of the true circle type 1 catheter. Consequently, the features of the arterial side opening on catheters can represent significant causative factors for suction against vessel walls.

Differences in arterial pressure

Against our expectation, the lowest arterial pressure observed in our experiments was with the true circle type 2 catheter, which also showed the lowest frequency of suctioning towards the vessel wall. In contrast, the highest arterial pressure was recorded with the semi-circle type 2 catheter, which also showed the largest frequency of suctioning towards the vessel wall.

We believe that the true circle type 2 catheter showed the lowest arterial pressure because it also had the smallest arterial side section area (3.2 mm^2). In our experiments, the arterial pressure of the true circle type 2 catheter was lower than that of the true circle type 1 catheter, despite these catheters exhibiting the same sectional area on the arterial side. At present, we cannot explain this difference and need to carry out further investigations. The highest arterial pressures were associated with the semi-circle type 2 catheter; this may be the result of this catheter exhibiting the thickest (13 Fr) outer diameter and the smoothest blood flow. Collectively, our present data suggest that we should measure arterial pressure in the proximity of the catheter opening area on the arterial side given that factors such as the shape and position of the opening area can exert affect.

Conclusions

We established a novel ex vivo catheter evaluation system using venous vessels from a pig. This system allowed us to reproduce catheter suction towards vessel walls in vivo. In addition, suctioning towards the vessel wall was easy to improve and was dependent upon the catheter structure with end hole and side hole.

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The data will not be shared.

Authors' contributions
YT participated in the design of this study and drafted the manuscript. JK and SY considered the experimental system. TO and IN kindly reviewed and revised the manuscript. All authors read and approved the final manuscript.

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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