Do Catheter Side Holes Provide Better Blood Flows?

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Four catheters (Ash Split Cath, Tesio, Duo-Split, and Duo-Flow; Medcomp, Harleysville, PA, U.S.A.) were tested in a temperature-controlled in vitro *setup filled with 50% aqueous glycerin solution to determine hydraulic resistance at different flow rates. All these catheters have side holes; hydraulic resistance was determined with these holes open and closed. Due to extra pressure losses near the catheter tip, the pressure–flow relationship deviates from Poiseuillian theory and is generally quadratic in nature. An equivalent diameter was derived from the data. This equivalent diameter can be used to evaluate performance using a single number.*

Permanent catheters can easily deliver 300 mL/minute under optimal circumstances, but acute catheters are, in practice, limited to 200 mL/minute, and even somewhat less in the coaxial Duo-Flow type. Permanent catheters have larger equivalent internal diameters (1.8 vs 1.45 mm). Covering the side holes does not influence hydraulic resistance to a great degree, except in the arterial limb of acute catheters.

These results indicate that, especially in acute catheters, obstruction of the side holes or fibrin sleeve/thrombus formation over the inlet holes may severely impact the available blood flow rate during dialysis. On the other hand, side holes in permanent catheters or venous limbs seem to be superfluous for performance reasons.

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Key words

Catheter, side holes, performance, equivalent diameter

Introduction

Central venous catheters have earned their place among the different methods of vascular access for hemodialysis (HD). Apart from their use in situations where immediate access to the blood is required [1,2], catheters are increasingly employed for the delivery of dialysis to patients with end-stage renal disease [3]. This has increased interest in the performance of catheters to provide adequate dialysis and, consequently, guidelines have been set forth [4]. The National Kidney Foundation-Dialysis Outcomes Quality Initiative (NKF-DOQI) guidelines [5] set the lower limit to 300 mL/minute for extracorporeal blood flow to be able to treat the patient without the need to increase the duration of the procedure. Yet, due to frequent infection and thrombosis, catheters show the lowest patency rate of all current methods of HD access [6]. Thrombus formation in most cases is easily remedied by means of a thrombolytic agent [7,8]. However, infection is a more severe problem, the rate of which depends not only on catheter handling [9,10] in the dialysis unit and by the patient, but also on the biocompatibility of the catheter material [11–13]. The same accounts for thrombogenesis on the inner or outer surface of the catheter [14], although local hemodynamics also plays a role in this process [15].

Catheters serve a simple purpose: to guide the venous blood towards the HD machine and bring it back into the venous system in a safe and reliable way. Therefore, it is remarkable that the geometrical designs of their blood conduits and tips differ substantially [16,17]. Different catheters are equipped with a number of side holes of various sizes and positions on the catheter wall. The common belief is that multiple side holes are needed to provide backup in case the apical or some of the side holes become obstructed by venous wall suction or a fibrin sleeve [14,17]. However, it has never been thoroughly investigated whether these side holes are able to allow the required blood flow rate. In addition, the absence of any adverse effects due to the presence of these holes has not been well studied. Schwarzmann and Sefrin [18] concluded that a catheter with multiple holes does not show any advantage as far as thrombogenicity is concerned. Twardowski and Moore [19] suggested that side holes predispose to formation of thrombi, as they observed, using scanning electron microscopy, rough edges of holes and clots firmly anchored to the holes of removed catheters.

The goal of the present study was to measure the performance of dual-lumen catheters in an *in vitro* setup by studying their pressure–flow relationships. We also investigated the influence of closing off some of the side holes to see if that would impact performance.

Materials and methods

To obtain reproducible pressure–flow relationships under standardized conditions, a dedicated *in vitro* measurement setup was built. The setup consisted of two reservoirs connected by

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two recirculation loops (Fig. 1). The upper reservoir's fluid level was kept constant by continuous recirculation from the bottom reservoir and an overflow tube. This ensured that a constant pressure of about 2 mmHg was present at the catheter tip. The second recirculation loop was made up partly of the catheter circuit; the other part was shared with the first recirculation loop. The catheter circuit either ran from the lower reservoir and through a dialysis roller pump to the venous lumen of the catheter, or it started at the upper reservoir and passed through the arterial lumen of the catheter and the dialysis roller pump to the lower reservoir. The circuit was filled with a 50%/50% aqueous solution of water and glycerin and kept at a constant temperature of 30°C using a controlled coil heater. This ensured that the viscosity remained constant at 4.8 mPa (or cP), slightly elevated to actual blood viscosity at normal hematocrits (40% – 45%) for reasons explained later. Dialysis patients have a similar blood viscosity due to elevated plasma viscosity, increased red blood cell (RBC) aggregation, and decreased RBC deformability [20].

Flow rate was determined using an ultrasound transit-time clamp-on flow meter (Transonic, Ithaca, NY, U.S.A.), 10-point calibrated for the glycerin solution by a gravimetric method over the total measurement range of 0 – 500 mL/minute. The pressure drop over the catheter was measured with a differential pressure transmitter (Fuji Electric, Erlangen, Germany) set to full scale (300 mmHg or 40 kPa). The pressure inputs of the transmitter were connected to the Luer lock of the lumen and to the constant level reservoir for reference. Both electronic devices were connected to a computer data-acquisition system (National Instruments, Zaventem, Belgium) for data processing.

The roller-pump speed was gradually adjusted to increase the flow rate through the catheter. To determine a single datum point, flow rates and pressures were recorded during a finite time, with a sampling rate of 200/second. Due to roller-pump operation, these curves exhibited a periodic pattern. To level out the pulsatility of the roller pump and the eventual unequal occlusivity of the two rollers, mean levels of flow rates and pressure differences were obtained by taking the average of an even number of periods. All averaged data points were used to fit a parabolic equation through the origin [Eq. (1)], stating the pressure drop (ΔP)–flow rate (Q) relationship of the catheter lumen. The parabolic equation was obtained by polynomial regression (SigmaPlot; SPSS Inc., Erkrath, Germany):

$$\Delta P = aQ + bQ^2. \quad (1)$$

Care was taken to ensure both parameters (a and b) of the fit equation were statistically significant ($p < 0.05$) to describe the data set. Performance can also be characterized by hydraulic resistance (R), which is not constant as the Poiseuille equation suggests, but is a linear function of the flow rate [Eq. (2)]:

$$R = \Delta P/Q = a + bQ. \quad (2)$$

To compare the different catheters in a standard manner, the concept of equivalent diameter (D_e) was used. The D_e is determined from the effective diameter (D_{eff}). The D_{eff} is defined as the internal diameter that a circular tube with the same length (L) as the catheter lumen should have, to exhibit the same pressure drop as the catheter under study at a particular flow rate. For laminar flow it is derived from the well-known Poiseuille equation and is defined by Eq. (3):

$$D_{eff} = (128\mu LQ/\pi\Delta P)^{1/4}. \quad (3)$$

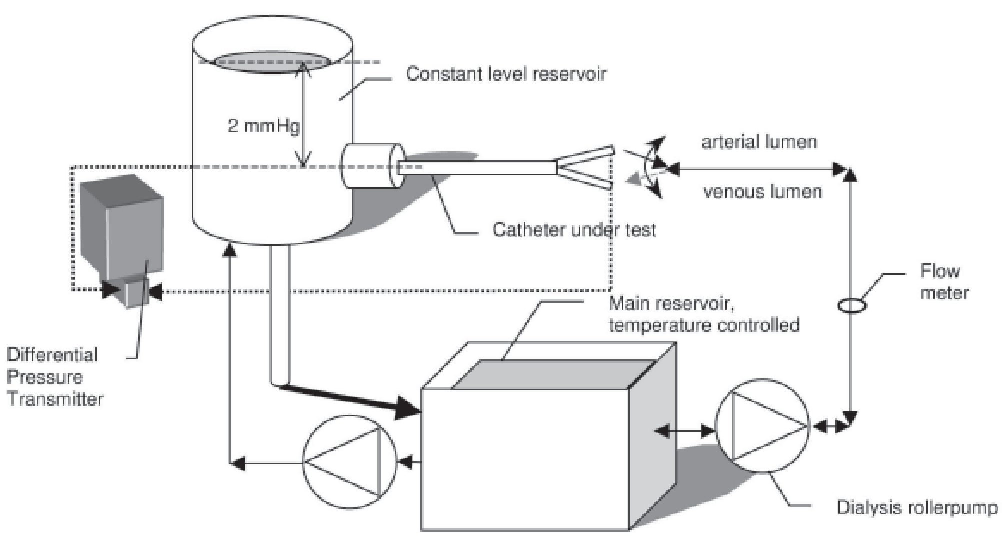

FIGURE 1 Overview of the measurement setup. The catheter tip is in the constant level reservoir. The dialysis pump either pumps the fluid into the venous lumen or draws it from the arterial lumen.

The D_{eff} should be independent of the fluid's dynamic viscosity (μ), as its effect is cancelled by the flow/pressure drop ratio. However, D_{eff} depends on the flow rate because of special pressure losses in the catheter that are not linearly proportional to the flow rate. For a reasonable approximation, it can be assumed that D_{eff} varies quadratically with the Reynolds number (Re). Therefore, the actual D_e is obtained in an iterative fashion as the D_{eff} at Re = 1000 on the polynomial regression line that is fitted through all D_{eff} in the laminar range. Reynolds number is defined as

$$Re = 4\rho Q/\pi D_e \mu, \quad (4)$$

where ρ is the density of the glycerin solution (1128 kg/m^3). Since the most correct results are obtained at equal Re numbers for blood and test fluid [21], and since the ratio of viscosity to density determines the Re number, a slightly elevated viscosity was used for the test fluid to correct for the higher density of the glycerin mixture with respect to whole blood. The higher the pressure drop is at Re = 1000, the lower the D_{eff} becomes. At Re = 1000, a flow rate of about 350 mL/minute was attained in this setup for the permanent catheters, and about 250 mL/min for the acute catheters.

In this study, four catheters with side holes were tested: two permanent [Ash Split Cath, 14 Fr/28 cm, and Tesio, 10 Fr/30 cm; Medcomp, Harleysville, PA, U.S.A.] and two acute (Duo-Flow, 11.5 Fr/20 cm, and Duo-Split, 12.5 Fr/20 cm; Medcomp). These catheters differ not only in the number and position of side holes, but also in basic geometry. The Ash Split Cath and Duo-Split are both double-D catheters [17]. The difference between these two catheters lies in the number of larger side holes: 2 in the Ash Split Cath and 6 in the Duo-Split. They both have a circular tip lumen with smaller diameter, but the Ash Split Cath has 6 small side holes and the Duo-Split has none. Twin Tesio catheters come with identical single-lumen pairs, each with 6 side-holes laid out in a spiral pattern. The Duo-Flow is a coaxial catheter with a tapered venous tip and 4 side holes for each lumen.

Different test runs were performed for each catheter: once with the intact catheter and then with some side holes masked with tape, thus effectively preventing any flow through them. For both the Ash Split Cath and the Tesio catheters, all side holes were closed; for the Duo-Split and Duo-Flow catheters, only two side holes in each lumen were masked because, otherwise, the flow rate would become too restricted in the Duo-Split and impossible in the Duo-Flow.

Results

As an example, in Fig. 2 the fitted parabolic equations for the Ash Split Cath measurements are shown, together with averaged data points. The fit lines follow the data points closely, with good correlation indices and small standard errors on the fit line parameters (*a*,*b*). Black symbols signify open side holes and white symbols closed holes. All curves lie close together; pressures are somewhat elevated with the side holes closed. The arterial curves (triangles) initially lie below the venous curves, perhaps due to their shorter length; however, due to extra pressure losses, the arterial curves are more quadratic and overtake the venous curves at around 400 mL/min.

As an example of hydraulic resistance, the results for the Tesio twin catheters are plotted in Fig. 3. In this measurement, the hydraulic resistance of arterial limbs is lowest at low flow rates, and highest at moderate to high flow rates. It should be noted that the effect of closing the side holes is expressed in the upward shift of the curves, with the greater effect in the arterial limb. This signifies that the *y*-intercept

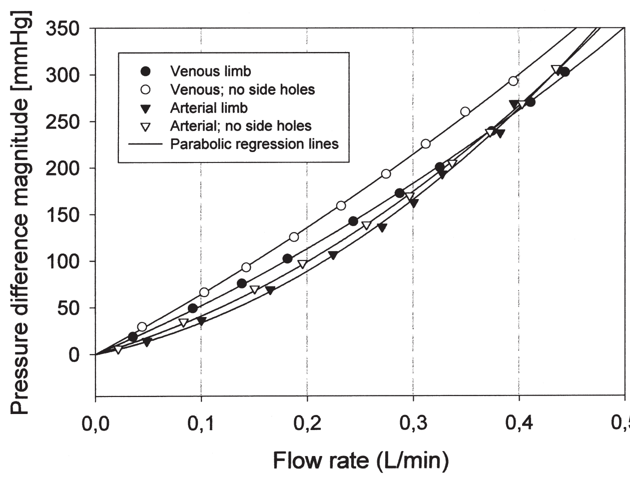

FIGURE 2 Measured and fitted quadratic pressure–flow relationships in both limbs (arterial: triangle; venous: circle) of the Ash Split Cath (Medcomp, Harleysville, PA, U.S.A.), with (black) and without side-holes (white).

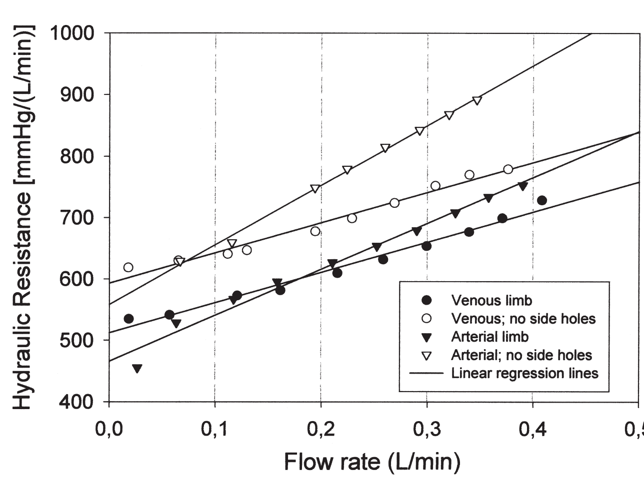

FIGURE 3 Hydraulic resistance in Tesio twin catheters (Medcomp, Harleysville, PA, U.S.A.) (arterial: triangle; venous: circle) is a linear function of the flow rate. At higher flow rates, higher resistances are found. Closing the side holes (white) shifts the regression lines obtained with open side holes (black) upwards, but does not alter slopes.

[constant *a*, Eq. (2)] has been increased by about 15% – 20%. As the quadratic content (influence of parameter *b*) in this catheter is small for the usual range of flow rates, this limited increase in intercept has only a mild effect on pressure drop [Eq. (1)].

The calculated D_e's are listed in Table I. A clear distinction can be made between the larger and longer permanent catheters and the smaller and shorter acute catheters. The permanent catheter group has an D_e of about 1.8 mm (internal diameter). A tube with this size and an assumed typical wall thickness of 0.5 mm would correspond to about 8.5 Fr (outer diameter). The acute group has much lower D_e's, about 1.45 mm. (about 7.5 Fr outer diameter). Closing the side holes has nearly no effect in permanent catheters (maximum decrease of 5%) or in the venous limb of acute catheters. However, for the arterial limb of acute catheters, D_e decreases significantly (about 20%) when two holes are closed. Since in all catheters except the Duo-Flow, the tip geometry of both limbs is equal, and since this tip geometry has a major impact on performance, the same D_e is expected in each of these catheters. A small difference of 1% – 3% in favor of the venous limb is observed as outflow produces no or smaller special pressure losses compared to inflow.

The absolute value of the pressure drop over the length of catheters at a test fluid flow rate of 300 mL/min is listed in Table II. Again, a distinction can be made between acute and permanent catheters: in the latter, the pressure difference is usually below 200 mmHg, except when side holes are closed. However, even in this case, the increase in pressure difference is minor. In acute catheters, pressure differences greater than 300 mmHg are needed to maintain flows.

We measured the flow rates that can be obtained with a reasonable pressure drop of 200 mmHg over the catheter length (Table III). In the permanent catheters, a flow rate of over 300 mL/min is easily attained, but becomes slightly lower when the side holes are occluded. Contrary to what Table I may suggest, there is a performance difference between the coaxial catheter (Duo-Flow) and the double-D shaped design (Duo-Split). Without occlusion of the side holes, the former attains a 10% (venous limb) to 25% (arterial limb) lower flow rate than the latter.

Discussion

Our *in vitro* study comparing the performance of double-lumen HD catheters demonstrates that the D_e derived from the pressure–flow relationship in permanent catheters is larger than the diameter of acute catheters. Generally, in medical and dialysis-related literature, the pressure–flow relationship is described by Poiseuille's equation [22], which states that the pressure difference varies linearly with the flow rate and is inversely proportional to diameter to the fourth power. While this is true for the ideal case of a Newtonian fluid flowing

TABLE I Equivalent diameters in millimeters (percent difference) of catheters for both lumens.

Catheter[a]	*Holes*	*Arterial*	*Venous*
Permanent			
Ash Split Cath (14 Fr×28 cm)	Open	1.79	1.83
	All closed	1.77 (–1%)	1.77 (–3%)
Tesio (2×10 Fr×30 cm)	Open	1.79	1.81
	All closed	1.70 (–5%)	1.76 (–3%)
Acute			
Duo-Split (12.5 Fr×20 cm)	Open	1.42	1.47
	Two closed	1.10 (–23%)	1.47 (0%)
Duo-Flow (11.5 Fr×20 cm)	Open	1.38	1.45
	Two closed	1.15 (–17%)	1.45 (0%)

[a] Medcomp, Harleysville, PA, U.S.A.

TABLE II Pressure difference in mmHg (percent change) over the lumen lengths at 300 mL/minute flow.

Catheter[a]	*Holes*	*Arterial*	*Venous*
Permanent			
Ash Split Cath (14 Fr×28 cm)	Open	166	184
	All closed	174 (5%)	212 (15%)
Tesio (2×10 Fr×30 cm)	Open	209	197
	All closed	255 (22%)	223 (13%)
Acute			
Duo-Split (12.5 Fr×20 cm)	Open	345	320
	Two closed	990 (187%)	321 (0%)
Duo-Flow (11.5 Fr×20 cm)	Open	433	382
	Two closed	751 (73%)	418 (9%)

[a] Medcomp, Harleysville, PA, U.S.A.

TABLE III Flow rate in milliliters per minute and (percent change) through the lumens at a pressure difference of 200 mmHg.

Catheter[a]	*Holes*	*Arterial*	*Venous*
Permanent			
Ash Split Cath (14 Fr×28 cm)	Open	337	322
	All closed	330 (–2%)	286 (–11%)
Tesio (2×10 Fr×30 cm)	Open	290	303
	All closed	250 (–14%)	274 (–10%)
Acute			
Duo-Split (12.5 Fr×20 cm)	Open	209	198
	Two closed	99 (–53%)	196 (–1%)
Duo-Flow (11.5 Fr×20 cm)	Open	155	178
	Two closed	92 (–41%)	169 (–5%)

[a] Medcomp, Harleysville, PA, U.S.A.

through a circular tube, and neglecting end effects, this is not true for catheters. Double-D shaped lumens also render a linear relationship as described by Poiseuille. The deviation from linearity in catheters is related to the extra pressure losses that occur at the entrance and exit of the catheter. Inflow through, or outflow from, side holes and tapered tips creates local velocity changes in both direction and magnitude. Hence, the pressure–flow relationship is quadratic, as shown for the Ash Split Cath in Fig. 2.

The D_e's (Table I) may seem rather small compared to actual diameters (*e.g.*, Tesio 8.5 Fr vs 10 Fr advertised). The reason for this phenomenon relates to the fact that D_e is based on performance characteristics, which include the effect of extra in- and outflow pressure losses. The total pressure difference is the sum of the Poiseuillian flow resistance, which increases linearly with the flow rate, and the effect of the extra resistance at inflow or outflow, which is proportional to the flow rate squared. According to Eq. (3), an increased pressure difference renders a lower D_e.

The concept of D_e is an interesting one, as it is a single parameter that allows comparison of pressure–flow data of different catheters independently from the test fluid used (and thus also independently of hematocrit and viscosity) and the length of the catheter. Longer catheters evidently require a higher pressure difference for equal flow rates. Therefore, the D_e is a direct measure of the performance of a catheter's design. This is especially useful for dual-lumen catheters as, for some designs (coaxial, double-D shaped), there exists no clear definition for the diameters of the individual limbs, which makes it harder to compare their geometrical data with two independent single-lumen catheters, such as, for example, the Tesio twin set. Catheters with the same lumen diameter and the same length but with a different D_e differ by the level of their specific pressure losses at in- and outflow. This may also be an indication for elevated shear stresses in these zones, which may affect the survival of blood cells.

For HD, 300 mL/min is recommended the minimum value for effective treatment [5]. Therefore, we tabulated (Table II) the required pressure differences over the catheter length (some extra pressure drop is generated in the dialysis circuit toward the blood pump). If patients have a lower Hct due to anemia, this pressure difference decreases proportionally with actual blood viscosity. In the acute catheters, pressure differences greater than 300 mmHg are required. These are not easily attained, even with modern dialysis equipment. It is very difficult, especially in the arterial limb, to attain 300 mL/min, as the very low pre-pump pressures that are needed would severely limit the actual blood flow rate [22]. The pressures required to draw 300 mL/min through acute catheters with a reduced number of side holes are completely out of range. This indicates the weak point of these catheters: development of a fibrin sleeve over the catheter's tip or thrombus formation near the side holes would severely limit the flow rate through these holes and consequently through the catheter as a whole.

As already indicated in Fig. 2, the results in Tables I – III clearly show that closing the side holes of permanent catheters, or the venous limbs of the tested acute catheters, has only a minor effect on the performance of the catheter. Side holes are required, however, at the inflow tip of acute catheters. The decrease in flow rates shown in Table III, especially in the arterial limbs of the tested acute catheters, may be due partly to the difference in actual diameters (11.5 Fr Duo-Flow and 12.5 Fr Duo-Split result in 3% difference in D_e), but the much larger difference in flow rate (–25%) for the arterial lumens between these two catheters is by design. Coaxial catheters generally have poor performance of the arterial (outside) lumens. The effect on the pressure differences, listed in Table II, may seem somewhat higher than the differences showed in the Tables I and III, but this is merely an indication that a small diameter change has a much greater effect on pressure difference due to the fact that pressure difference is inversely proportional to diameter to the fourth power. For example, a 2.5% decrease in diameter will cause a 10% increase in pressure difference.

The findings of this study imply that side holes can be eliminated from permanent catheters, and that the number of side holes may be decreased in the venous limbs of acute catheters. Use of side holes may provoke other problems as well. It has been reported that the vein intima may be sucked into the lumen of the catheter through the side holes, especially when the tip hole is obstructed [19]. Side holes may enhance recirculation between the limbs of dual-lumen catheters, which triggers the manufacturers to separate the lumen tips or to position the side holes on opposite sides [17]. Leaching of locking solutions may enhance the formation of blood clots, as are frequently observed at the tip and side holes of catheters [19]. When vein intima is sucked, the pre-pump pressure and, consequently, blood flow through the dialysis machine decreases significantly. As recirculation is a dynamic process that depends not only on the geometrical design of the catheter, but also on its position in the vicinity of the right atrium and on cardiac input flow [23], it currently cannot be determined in our model. For similar reasons, it is difficult to use these data to comment on the leaching of anticoagulants between treatments [19], as this process depends on catheter tip movement and position in the right atrium [24] and density differences between blood and locking solution.

One last disadvantage of catheter side holes is the formation of blood clots. Clots may be firmly anchored to the catheter around the side holes [18,19]. As some of these holes have a small diameter and therefore a much greater wall surface-to-flow area ratio, only limited force can be applied to remove the clots *in situ*.

The clinical importance of potential problems caused by side holes is not clear. It should be noted that performance might not be the only reason to use side holes in catheters. No information about their use and performance as a backup for (partial) occluded or malpositioned catheters is known to us. However, in our view, occluded tips should always be opened, for a clot or fibrin sleeve may be the cause of hemolysis [25]. Tips that are stuck against the wall can be freed by applying positive pressure on the limb. Malpositioned catheter tips will always have less than optimal performance. Preliminary studies comparing permanent catheters, with limited patient-catheter days, did not show an important advantage of different tip designs [26]. For permanent catheters, where the side holes do not increase the performance and therefore have limited blood flows through them, with zones of low shear, clot attachment may possibly be enhanced [15].

Conclusion

Our analysis of different catheters for hemodialysis treatment demonstrates that multiple side holes, generally and under the ideal circumstances of the presented *in vitro* setup, do not improve catheter performance, except for inflow in acute catheters. The equivalent diameter derived from the pressure–flow relationship of permanent catheters is larger than the diameter of acute catheters, and double-D catheters perform better than coaxial designs. These findings should be taken into account when developing new catheters. More clinical studies are needed to confirm the implications of our findings in the practice of hemodialysis.

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