Computational Modelling Based Recommendation on Optimal Dialysis Needle Positioning and Dialysis Flow in Patients With Arteriovenous Grafts

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Computational Modelling Based Recommendation on Optimal Dialysis Needle Positioning and Dialysis Flow in Patients With Arteriovenous Grafts

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WHAT THIS PAPER ADDS

This work has demonstrated that blood flow near the venous anastomosis of arteriovenous grafts deteriorates considerably as a result of flow from the venous dialysis needle. Since disturbed flow is believed to be the initiating event of venous neointimal hyperplasia, this finding suggests that dialysis needle flow can play an important role in graft patency loss. The negative effects of dialysis flow can be mitigated by ensuring the venous needle is in the centre of the graft's lumen, by decreasing dialysis flow, or by increasing the distance between graft cannulation and the venous anastomosis.

Objective: Arteriovenous grafts (AVGs) typically lose patency within two years of creation due to venous neointimal hyperplasia, which is initiated by disturbed haemodynamics after AVG surgery. Haemodialysis needle flow can further disturb haemodynamics and thus impact AVG longevity. In this computational study it was assessed how dialysis flow and venous needle positioning impacts flow at the graft-vein anastomosis. Furthermore, it was studied how negative effects of dialysis needle flow could be mitigated.

Methods: Non-physiological wall shear stress and disturbed blood flow were assessed in an AVG model with and without dialysis needle flow. Needle distance to the venous anastomosis was set to 6.5, 10.0, or 13.5 cm, whereas dialysis needle flow was set to 200, 300 or 400 mL/min. Intraluminal needle tip depth was varied between superficial, central, or deep. The detrimental effects of dialysis needle flow were summarised by a haemodynamic score (HS), ranging from 0 (minimal) to 5 (severe).

Results: Dialysis needle flow resulted in increased disturbed flow and/or non-physiological wall shear stress in the venous peri-anastomotic region. Increasing cannulation distance from 6.5 to 13.5 cm reduced the HS by a factor 4.0, whereas a central rather than a deep or superficial needle tip depth reduced the HS by a maximum factor of 1.9. Lowering dialysis flow from 400 to 200 mL/min reduced the HS by a factor 7.4.

Conclusion: Haemodialysis needle flow, cannulation location, and needle tip depth considerably increase the amount of disturbed flow and non-physiological wall shear stress in the venous anastomotic region of AVGs. Negative effects of haemodialysis needle flow could be minimised by more upstream cannulation, by lower dialysis flow and by ensuring a central needle tip depth. Since disturbed haemodynamics are associated with neointimal hyperplasia development, optimising dialysis flow and needle positioning during haemodialysis could play an important role in maintaining AVG patency.

Keywords: Arteriovenous graft, Cannulation, Dialysis, Disturbed flow, Venous needle
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INTRODUCTION

Arteriovenous grafts (AVGs) typically lose patency within two years due to neointimal hyperplasia (NIH) at the graft-vein anastomosis,[1–3] which is attributed to disturbed blood flow and non-physiological wall shear stress (WSS) after AVG creation. Most research on minimising disturbed flow and normalising WSS patterns at the graft-vein anastomosis has focused on modifying graft geometry.[4] Strikingly, the impact of haemodialysis (HD) needle flow on AVG haemodynamics is often neglected, even though it has been shown that needle flow can result in increased flow disturbance.[5–7] Most HD patients receive dialysis according to intermittent or daily dialysis programs that amount to 12–36 h per week. Consequently these patients are exposed to the possibly detrimental haemodynamic effects of dialysis needle flow for 10%–30% of their time. It is therefore conceivable that also dialysis needle flow plays an important role in AVG dysfunction.[8] Minimising disturbed

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flow by optimising cannulation technique and dialysis flow rate might therefore be beneficial to graft longevity. In this study was assessed how dialysis flow rate, needle tip location in the graft's lumen (needle tip depth), and the site of graft cannulation (cannulation location) impact AVG haemodynamics at the venous anastomosis. The effect of dialysis needle flow was assessed using a computational fluid dynamics (CFD) model of an idealised geometry of the venous anastomosis of an AVG.

MATERIALS AND METHODS

A model of the venous anastomosis of an AVG was created in SolidWorks 2017 (Dassault Systèmes, Vélizy-Villacoublay, France) (Fig. 1A). The vein was modelled as a straight, 15 cm long vessel with a constant diameter of 7.7 mm. The graft segment was 20 cm long, with a 6 mm internal diameter. The graft-vein anastomosis had an angle of 45°. The resulting length of the anastomosis was approximately 9 mm. Vascular dimensions were based on standard of care ultrasound follow up for monitoring graft function.

Cannulation model

In clinical practice the location of the AVG venous cannulation site is changed between HD sessions to ensure that a maximum length of the graft's venous segment is used for cannulation.[3,9] This practice is known as the rope ladder technique and was modelled by setting the distance between the needle tip and the anastomosis to 6.5, 10.0, and 13.5 cm. The cannulation procedure was modelled as described in Brouwer.[10] The shaft of a standard one inch 15 G steel needle was advanced completely through the skin. The needle tip was positioned bevel down in the lumen.[10] Needle back eye was omitted since it minimally impacts haemodynamics.[11] Intraluminal needle tip location was either in the graft's cross sectional centre or 1.5 mm above or below, corresponding to a superficial or deep needle tip depth, respectively (Fig. 1A). It was assumed that the graft was located 3 mm beneath the skin. Consequently, resulting cannulation angles for the superficial, central, and deep needle tip depth were 9.2°, 13.9°, and 17.5°, respectively. Dialysis flow rate was set to 200, 300, or 400 mL/min. All 27 combinations of dialysis flow, needle tip depth, and cannulation location were evaluated, next to a reference AVG simulation without needle.

In this study, blood was regarded as a Newtonian fluid with a density of 1 000 kg/m^3 and a viscosity of 3.5 mPa s.[12] Pulsatile flow through the model (q_{total}) was assumed to be equal in all simulations and was obtained from the duplex ultrasound measurements (Fig. 1B). The average magnitude of the total graft flow was measured as 9.9×10^2 mL/min. Needle and graft flow were set by prescribing a blunt velocity profile at the respective inlet. Graft flow (q_{graft}) was defined as $q_{\text{total}} - q_{\text{needle}}$. Because flow from the distal veins was assumed to be negligible, blood flow velocity at the distal venous inlet was set to zero. A zero pressure was prescribed at the venous outlet, since flow velocity and wall shear stress (WSS) characteristics were independent of the outlet pressure in this modelling set up. After an initial start up of the simulation, haemodynamics had stabilised from the third cardiac cycle onwards and did not vary between subsequent cycles. Therefore, for all situations three cardiac cycles were simulated of which the final one was considered representative of the simulated condition. This cycle was subsequently used for all further analyses.

Computed haemodynamic metrics

Disturbed flow was quantified in each simulation by assessing the magnitude of high frequency velocity perturbations in both the venous anastomotic region and in the proximal vein (Fig. 1). Furthermore, the amount of non-physiological WSS was quantified by assessment of the size of the area exposed to wall shear stress (WSS) below or above the physiological range (0.1—7 Pa);[13] to WSS levels causing irreversible endothelial damage (>40 Pa);[14] or to highly oscillating WSS (oscillatory shear index > 0.25).

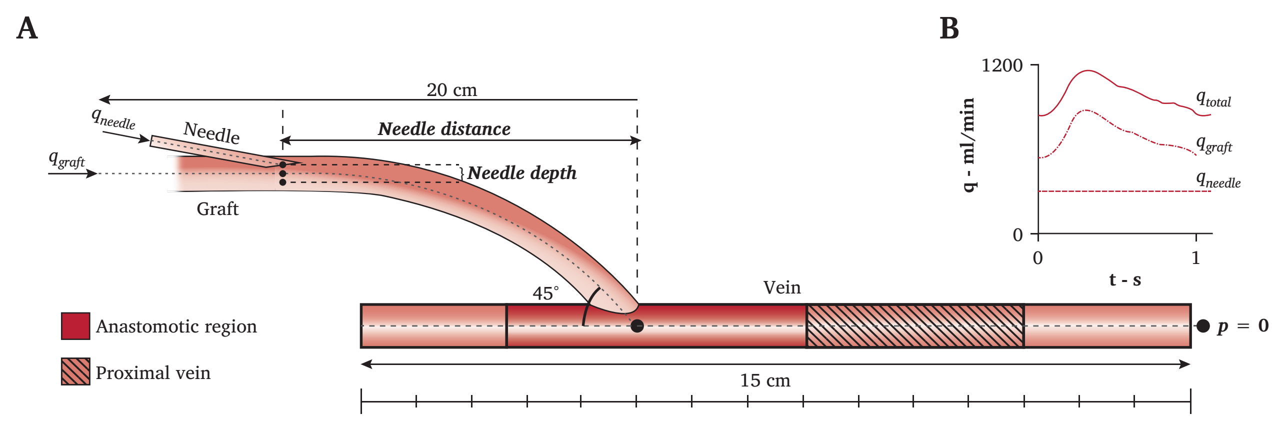

Figure 1. (A) The arteriovenous graft model. Note that the needle is only included when haemodialysis is simulated. Needle flow was set to 200, 300 or 400 mL/min, needle tip distance was set to 6.5, 10.0 or 13.5 cm from the anastomosis and the needle tip was placed in the centre of the graft or 1.5 mm above or below the centre (superficial and deep needle tip depth, respectively). (B) Overview of the simulation flows. Note that q_{total} is constant between simulations, whereas q_{graft} depends on q_{needle}. q = graft flow. $p = 0$ is meant to indicate that the pressure at the venous outlet is 0 mmHg.

A detailed description of the computational fluid dynamics model and formulation of the computed haemodynamic metrics is presented in the Supplementary material.

Haemodynamic scoring of needle impact

To allow for comparison of the haemodynamic effects of different HD settings, a scoring technique was devised that combined the overall haemodynamic effect into a single variable. This haemodynamic score quantified how much the haemodynamics in a simulation with a dialysis needle had deteriorated with respect to the reference simulation. The haemodynamic score used in this paper was computed on the basis of five variables related to graft dysfunction, i.e. the size of the anastomotic area exposed to non-physiologically low WSS (<0.1 Pa); to non-physiologically high WSS (>7 Pa, $\leq$ 40 Pa); to very high WSS (>40 Pa); or to high oscillatory shear index (OSI) (>0.25), as well as the magnitude of velocity perturbations in the anastomotic and proximal venous region. The total area of the anastomotic region of the model (Fig. 1) was 1 256.5 mm^2. A haemodynamically relevant deterioration or improvement of any WSS metric was defined as an increase or decrease in size of the exposed area of at least 5% of the total size of the anastomotic region (i.e. $>$ 62.8 mm^2) compared with the reference simulation. A haemodynamically relevant increase or decrease in the amount of disturbed flow was defined as a difference in the magnitude of velocity perturbations of at least 2 cm/s with respect to the reference simulation.

For each haemodynamic metric that showed a relevant deterioration in a simulation, the haemodynamic score was incremented by 1. Conversely, the score was decreased by 1 for each haemodynamic metric that showed a relevant improvement compared with the reference simulation. Finally, an average haemodynamic score was computed for all simulations that either shared the same tip depth, dialysis flow, or cannulation location. Since all combinations of flow, needle tip depth and cannulation location were evaluated, each average haemodynamic score was computed on the basis of nine simulations.

Table 1. Anastomotic area percentage exposed to high (>7 Pa) and very high (>40 Pa, in brackets) wall shear stress for each dialysis setting

Dialysis flow	Cannulation location	Needle tip depth		
		Superficial	Central	Deep
200 mL/min	6.5 cm	43$^+$	44$^+$	30
	10.0 cm	43$^+$	31	28
	13.5 cm	34	36	36
300 mL/min	6.5 cm	56$^+$ (1)	47$^+$	48$^+$
	10.0 cm	40$^+$	32	46$^+$
	13.5 cm	34	34	42$^+$
400 mL/min	6.5 cm	49$^+$ (13$^+$)	49$^+$ (1)	46$^+$
	10.0 cm	41$^+$	40$^+$	44$^+$
	13.5 cm	37	33	41$^+$

A superscript + denotes a relevant increase compared with the reference simulation.

Table 2. Anastomotic area percentage exposed to low (<0.1 Pa) wall shear stress for each dialysis settings

Dialysis flow	Cannulation location	Needle tip depth		
		Superficial	Central	Deep
200 mL/min	6.5 cm	31$^+$	28$^+$	21
	10.0 cm	17	19	18
	13.5 cm	19	17	16
300 mL/min	6.5 cm	24	19	26$^+$
	10.0 cm	21	22	27$^+$
	13.5 cm	22	19	22
400 mL/min	6.5 cm	23	18	26$^+$
	10.0 cm	20	30$^+$	26$^+$
	13.5 cm	28$^+$	24	24

A superscript + denotes a relevant increase compared with the reference simulation.

RESULTS

General observations

Wall shear stress. In the reference simulation, the area exposed to high (>7 Pa), low (<0.1 Pa) and highly oscillatory (OSI $>$ 0.25) WSS amounted to 32%, 20%, and 3% of the anastomotic area, respectively. No WSS in excess of 40 Pa was observed.

A relevant increase in the area subjected to high WSS was observed for all simulations using a 6.5 cm cannulation location, except when using a 200 mL/min needle flow, in combination with a deep needle tip depth (Table 1). Only when needle flow was set to 400 mL/min and cannulation was in close vicinity of the anastomosis (6.5 cm) with a superficial needle tip depth, a relevant area exposed to very high WSS (>40 Pa) was observed. In general, a central needle tip depth combined with more distal (away from the anastomosis) cannulation most efficiently lowered maximum WSS to reference conditions for the 300 and 400 mL/min needle flows. Although relevant increases in the anastomotic area exposed to low time averaged wall shear stress (TAWSS) and high OSI were observed in some simulations (Tables 2 and 3), no clear general trends with respect to cannulation location, needle tip depth or dialysis flow were observed.

Table 3. Anastomotic area subjected to high (>0.25) OSI for each dialysis settings

Dialysis flow	Cannulation location	Needle tip depth		
		Superficial	Central	Deep
200 mL/min	6.5 cm	4	16$^+$	3
	10.0 cm	8	2	2
	13.5 cm	2	1	1
300 mL/min	6.5 cm	10$^+$	5	8
	10.0 cm	1	3	6
	13.5 cm	2	2	5
400 mL/min	6.5 cm	20$^+$	9	12$^+$
	10.0 cm	2	9$^+$	10$^+$
	13.5 cm	5	10$^+$	10$^+$

A superscript + denotes a relevant increase compared with the reference simulation.

Disturbed flow. An increase in the magnitude of flow disturbances in the venous segment could be observed with more proximal cannulation sites (towards the anastomosis), higher dialysis flow settings and when the needle tip was not placed in the centre of the graft's lumen (Figs. 2 and 3). When the needle was placed centrally in the graft's lumen, flow perturbations were, in general, similar or lower to those observed in the reference simulation.

Haemodynamic scoring. The lowest haemodynamic scores were obtained by using a central needle tip depth, a 200 mL/min dialysis flow and a 13.5 cm cannulation distance (Fig. 2, Table S1). When using a superficial or deep needle tip depth instead of a central needle tip depth, the haemodynamic score increased on average by a factor 1.2 and 1.9, respectively. Furthermore, the average haemodynamic score increased by a factor 4.0 and 7.4 when using a 300 mL/min and 400 mL/min, instead of 200 mL/min dialysis flow, respectively. Finally, decreasing the cannulation distance from 13.5 cm to 10.0 cm or 6.5 cm increased the average haemodynamic score by a factor 2.4 and 4.0, respectively.

DISCUSSION

This study has shown that venous HD needle flow can considerably impact the amount of non-physiological and highly oscillating WSS experienced by the venous peri-anastomotic region of AVGs. Furthermore HD needle flow induces disturbed flow in, and downstream of, the AVG's venous anastomosis. This is of particular interest as both disturbed flow and disturbed WSS are believed to be the main initiators of NIH development in the venous anastomotic region, which is the primary cause of AVG failure.[1,15] Since HD is performed for a considerable amount of a dialysis patient's time, this study thus suggests that haemodialysis needle flow plays an important role in the process of AVG dysfunction. Indeed, increased AVG longevity is observed in VAs that are not being used, compared with those that are.[16]

A haemodynamic score was used to isolate the haemodynamic effects of varying dialysis flow, cannulation location and needle tip depth. As such, this score was used to identify optimal settings for each individual dialysis parameter, regardless of the setting of the other two. It was demonstrated that the negative effects of dialysis needle flow could best be mitigated by decreasing dialysis flow, more upstream cannulation and/or by ensuring a central needle tip depth.

Because a central needle tip depth showed the least negative impact on anastomotic haemodynamics, this study adds an additional haemodynamic argument for existing clinical recommendations that advocate placing the needle tip in the centre of the graft's lumen, to prevent needle infiltration of the graft wall. Since recent research shows that the needle tip is only in the graft's centre in 10% of all

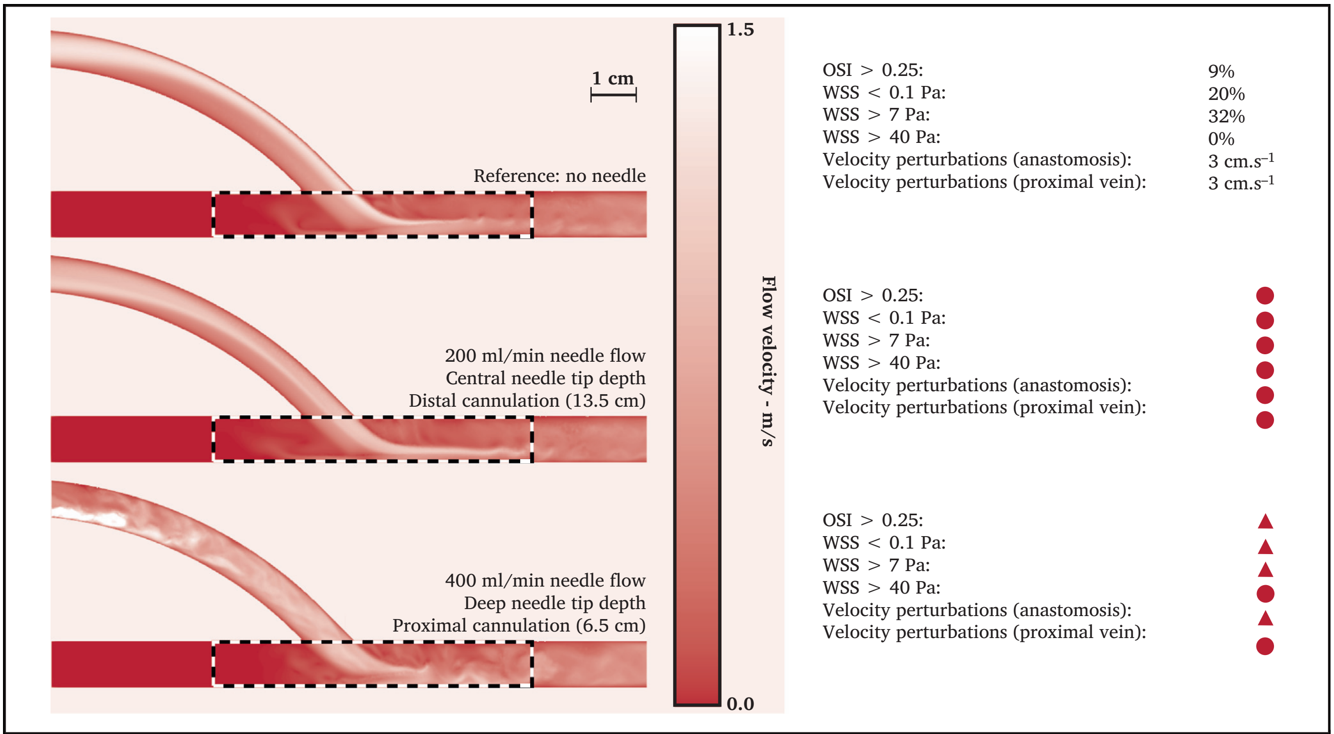

Figure 2. Left: Comparison of the flow fields observed in the reference flow simulation (top), a simulation with a low haemodynamic score (middle) and a simulation with a high haemodynamic score (bottom). For each simulation the anastomotic region is denoted by the dashed rectangle. For the reference simulation, percentages of the anastomotic area exposed to high OSI (>0.25), non-physiologically low (<0.1 Pa), high (>7Pa ≤ 40Pa) and very high WSS (>40 Pa) are presented on the right, along with the maximum observed magnitude of velocity perturbations. For the HD simulations, the triangles on the right denote which metrics showed a relevant deterioration with respect to the reference simulation, whereas the circles indicate which metrics did not show a relevant deterioration. WSS = wall shear stress; HD = haemodialysis.

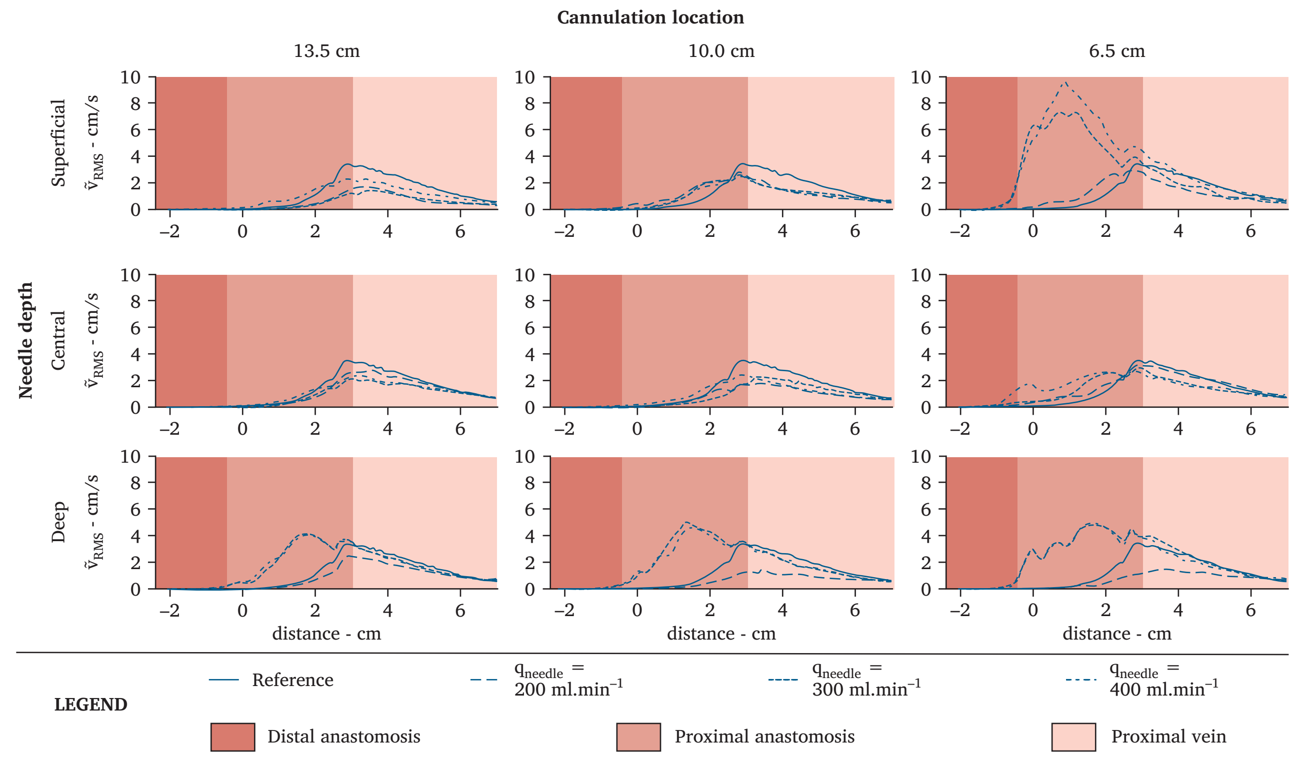

Figure 3. Cross sectional median magnitude of velocity perturbations along the venous centreline for all simulations. Each plot represents a different needle combination of needle tip depth and cannulation location. The reference simulation is represented in each plot by the solid blue line. Note that the anastomosis, indicated by the black dot in Fig. 1, is located at distance = 0 cm.

successful cannulations,[17] it is important to develop techniques that streamline the process of placing the needle tip in the centre of the graft's lumen. In this context, ultrasound guided cannulation might be a promising way of achieving this.[3] In addition, it should be investigated whether needle tip depth changes considerably during a dialysis session due to patient movement.[10,17] If so, it may be advantageous to develop methods to maintain a stable needle tip depth during dialysis.

In clinical practice AVGs are also cannulated in close proximity to the anastomosis, since grafts are cannulated over the greatest possible distance to prevent excessive local graft damage (rope ladder cannulation). Since this study demonstrated that haemodynamics deteriorate with more downstream cannulation, it might be necessary to find an optimal trade off between minimising graft damage due to cannulation and minimising detrimental haemodynamics. However, it should be ensured that the cannulation region remains sufficiently large to prevent pseudoaneurysm formation.[18] Alternatively, constructing the venous anastomosis more proximally on the vein could help create a longer venous graft segment, which might reduce the need for cannulation near the anastomosis.

Increasing dialysis flow had a clear negative effect on anastomotic haemodynamics. More specifically, of all evaluated HD settings, haemodynamics deteriorated most with a 400 mL/min dialysis flow, especially when cannulation was performed in close proximity to the venous anastomosis. It has been shown that autologous fistula survival is inversely correlated to dialysis flow.[19] Given the results of this study, a similar relation might hold true for AVGs.

In this study the effect of dialysis flow and needle positioning on anastomotic haemodynamics was assessed by a model comprising a standard 6 mm graft. However, alternative graft designs such as cuffed grafts have been specifically designed to optimise venous anastomotic haemodynamics.[20] The use of such modified grafts could possibly further help mitigate the negative effect of dialysis needle flow on anastomotic haemodynamics. Furthermore, though grafts are typically cannulated using metal needles,[21] it is suggested that the use of plastic cannulae could reduce dialysis flow induced flow disturbances.[22,23] Future research should be performed to assess the possible haemodynamic benefits of alternative graft designs and plastic cannulae during haemodialysis.

Limitations

As blood flow is dependent on patient specific properties, such as anastomotic angle and graft flow magnitude, exact haemodynamics will vary between patients.[24,25] However, since important flow characteristics of a vascular access is preserved in idealised models,[24] the observed negative effect of high dialysis flows, proximal cannulation, and non-central needle tip depth on AVG haemodynamics will translate to the general patient population. The current study employed a CFD model to assess the impact of needle flow on AVG haemodynamics related to AVG failure. However, the exact biological response on haemodynamic metrics is often unknown.[2,26] Consequently, future patient studies should be performed to confirm and quantify the clinical benefit of lower dialysis flows, central needle tip depths and more upstream cannulation.

CONCLUSION

In this study it was demonstrated that needle flow can substantially deteriorate haemodynamics at the venous anastomosis of AVGs. Since haemodynamics trigger NIH development, dialysis needle flow might play a considerable role in AVG dysfunction. The negative effect of needle flow can be minimised by having a greater distance between the cannulation site and the anastomosis, lower needle flows and a needle tip that is placed in the centre of the graft.

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CONFLICT OF INTEREST

None.

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APPENDIX A. SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejvs.2019.08.013.

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COUP D'OEIL

Superior Thyroid Artery Perforation During Carotid Artery Stenting

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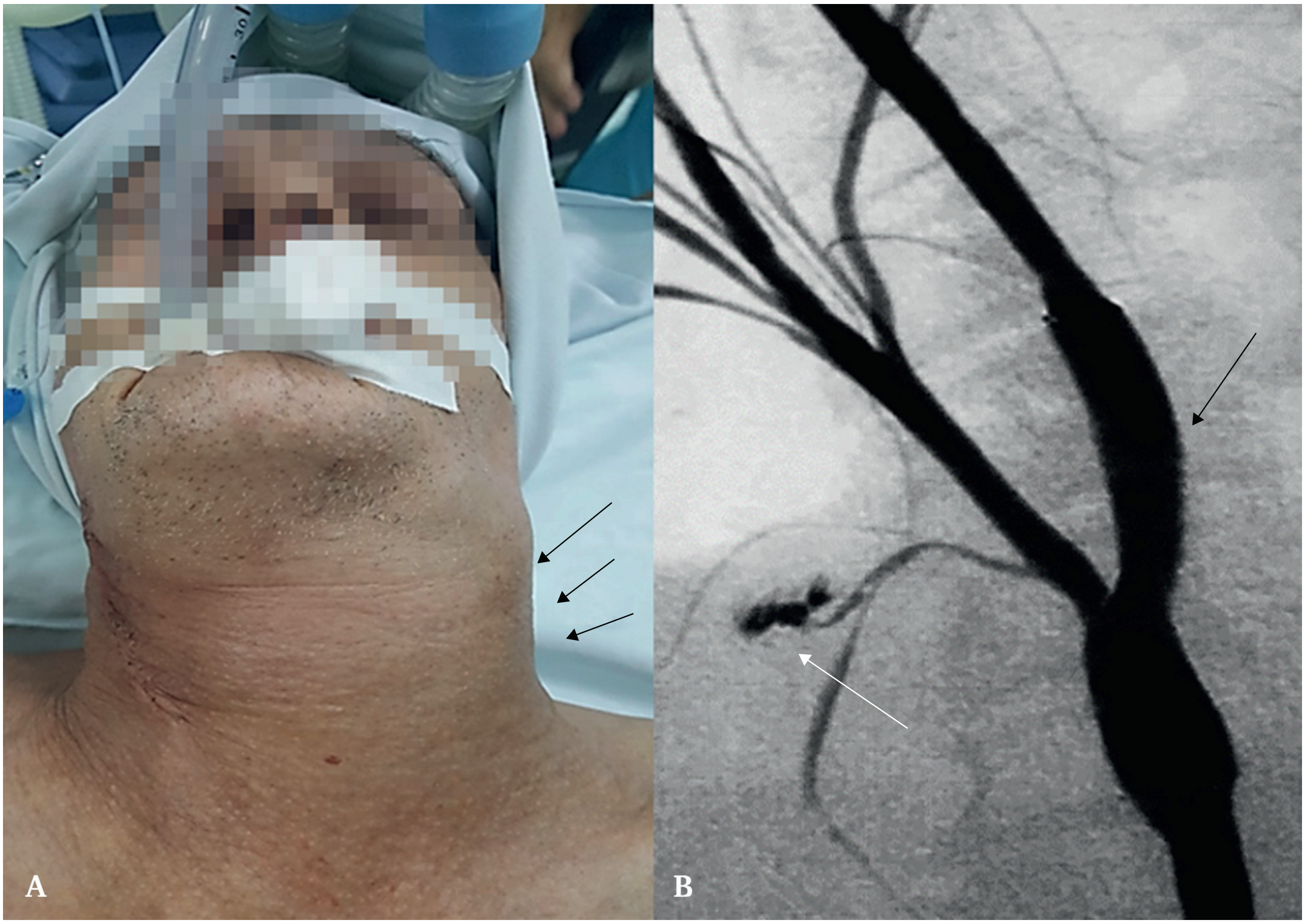

A hydrophilic guidewire (Terumo Radifocus® Guide Wire M Stiff type angled 0.035") was placed in the superior thyroid artery of a 62 year old male with bovine arch during left carotid artery stenting. At the end of the procedure he complained of throat discomfort. Increasing swelling developed on the left side of the neck (A, black arrows) and he was intubated because of dyspnoea. Check angiography (B) showed stent patency (black arrow) and extravasation from the superior thyroid artery (white arrow). Urgent surgery was performed with haematoma evacuation and superior thyroid artery ligation. The patient recovered fully.

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