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Original

Fluid Dynamics of Single-needle Dialysis in an Experimental Model

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ABSTRACT

Background : Acceptance has grown for single-needle dialysis when a vascular access is not suited for the insertion of two needles. Its impact on flow patterns was unknown.

Methods : We produced transparent life-size models of arteriovenous (AV) fistulas and AV grafts that we placed into a pulsatile flow system to examine flow characteristics during simulated dialysis cycles. For this purpose we injected dye, and recorded and analyzed the resulting flow patterns using suitable software tools.

Results : There is a definite flow reversal during the arterial phases in both AV fistulas and -less pronounced-in AV grafts leading to flow oscillations.

Conclusion : Flow oscillations initiate subintimal hyperplasia possibly leading to stenoses in vivo. Reversal of the flow direction may also cause steal phenomena in the poorly perfused distal extremity. Single-needle dialysis should therefore be avoided if possible.

Key words : hemodynamic patterns, single-needle dialysis, vascular access, intimal hyperplasia

INTRODUCTION

Single-needle (SN) hemodialysis is a therapeutic option used especially when blood removal and return are feasible via one needle only. Directly downstream from the single puncture needle, a y-shaped connector unites two lumina for either the arterial (withdrawal phase) or the venous (return phase) flow, respectively.

Although SN dialysis is less efficient than conventional double needle (DN) dialysis, SN dialysis has been accepted as one of the alternatives of renal replacement therapy[1)]. The impact of SN dialysis on the hemodynamics of an arteriovenous (AV) fistula or graft was unknown. This experimental study investigates the effects of SN dialysis on fluid dynamics using a simulated arteriovenous fistula and a simulated artificial graft, respectively. For this purpose, transparent silicone models were placed into a pulsatile flow system.

METHODS

The geometry of the transparent life-size silicone models that we produced corresponds to the idealized image of AV vascular accesses[2)]. For model AV prosthestic grafts, a venous end-to-side anastomosis was imitated 20 cm downstream from the model arterial anastomosis (Figure 1a). For model AV fistulas , the model venous branch running to the imaginary distal extremity was occluded (Figure 1b). The diameters

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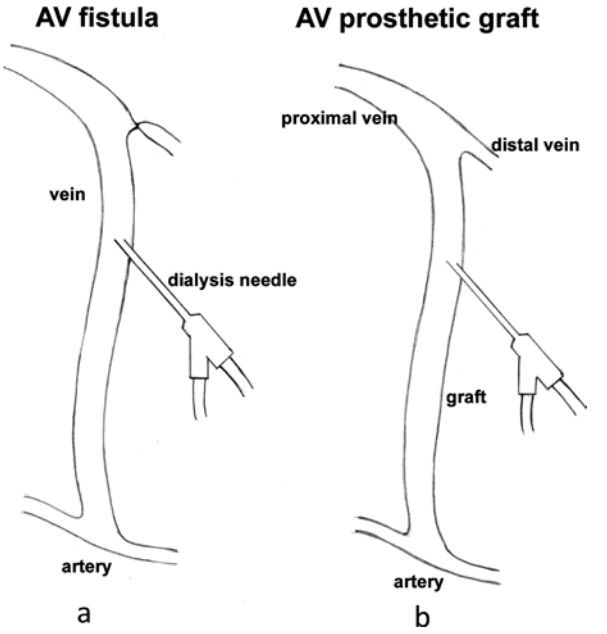

Figure 1 Sketches of the silicone models inserted into the pulsatile flow system. **a** : Model AV fistula. **b** : Model AV prosthetic graft.

of the model veins for puncture and the simulated graft diameters were 7 mm, and the model arterial diameter was 4 mm.

The models were placed into a pulsatile flow system. The model liquid that we used was an aqueous glycerol solution which had the same viscosity as whole blood. The ratio of water to glycerol was 42.5% to 57.5%[3]. For the simulation of hemodialysis, a BM-11 dialysis machine (Baxter, Deerfield, IL, USA) was used. The pressure thresholds of the dialysis machine were set to 120 mmHg (low) and 220 mmHg (high). The mean dialyzer flow for SN dialysis was set to 200 ml/min resulting in a peak flow of approximately 400 ml/min in the arterial line corresponding to a venous peak flow of −400 ml/min during the return phase.

Flow patterns were visualized by direct dye injection (Marabu silk art, Marabu Gmbh & Co KG, Bietigheim-Bissingen, Germany). For investigations concerning model AV fistulas, red dye was injected into the proximal tube of the model artery, and green dye was injected into the distal tube of the model artery close to the fake arterial anastomosis (AV fistula, Figures 2 a and b). For investigations of the model AV-grafts, the dye was injected using an additional thin needle placed 1.5 cm downstream from the

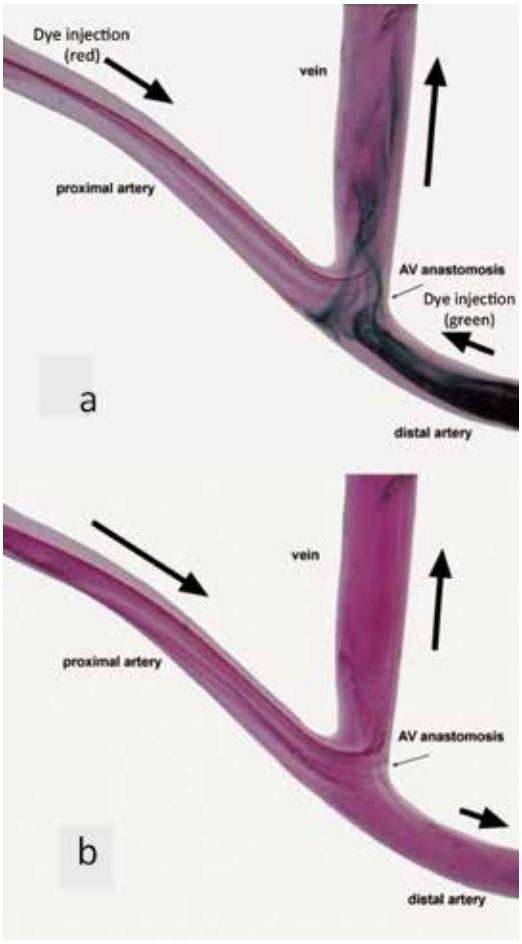

Figure 2 Flow patterns within the model artery and AV fistula. **a** : arterial phase. **b** : venous phase.

constant site of the single dialysis needle. (Figures 3 a and b).

The distribution of the dye after injection was recorded by a digital video camera (MV1, Canon, Inc., Tokyo, Japan. The mean arterial inflow into the model AV fistulas was set to 350 ml/min as determined by the setting of the pulsatile flow system. For the investigations of the model AV prosthetic grafts, a higher inflow of 600 ml/min was chosen.

RESULTS

We present the results of four typical constellations :

1. AV fistula, arterial phase (Figure 2 a)

During late diastole of the pulsatile flow system, the flow within the distal model artery of the AV fistula changes its direction. The green particles are drawn

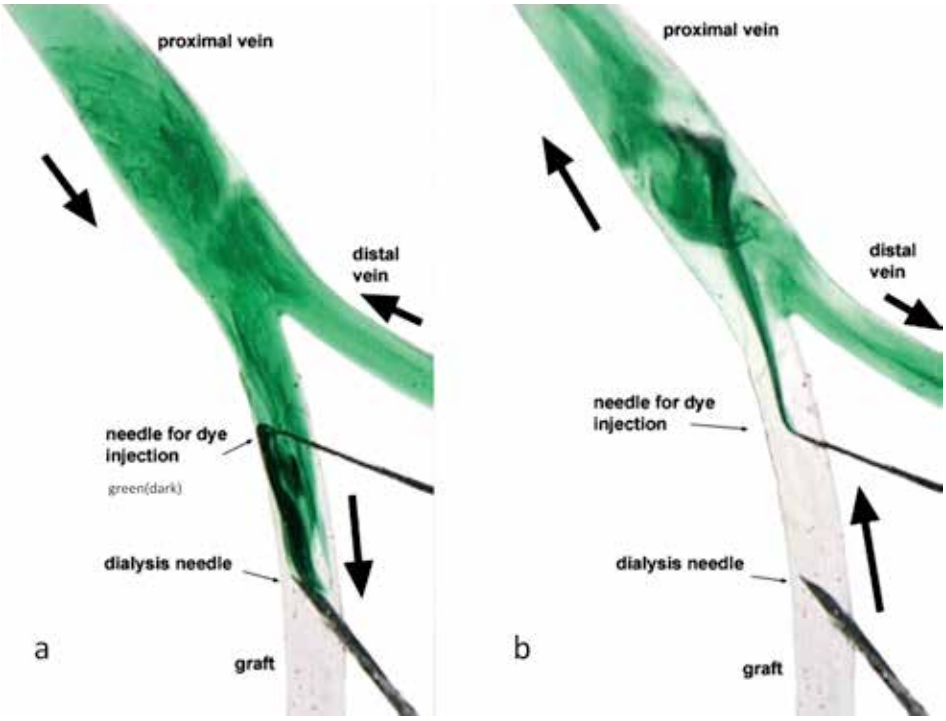

Figure 3 Flow patterns within the venous anastomosis of a model AV prosthetic graft. **a** : arterial phase (late diastole). **b** : venous phase.

into the dialysis needle passing through the anastomosis and the adjoining model vein.

2. AV fistula, venous phase (Figure 2 b)

Figure 2 depicts the systolic flow patterns in the AV fistula as described in the literature [4, non-tapered graft] (vortex within the venous entry of the anastomosis caused by the lateral portions of the stream). There is no retrograde flow at all.

3. AV graft, arterial phase (Figure 3 a)

During late diastole of the pulsatile flow system and the arterial phase of the dialysis machine, the flow within the entire model venous anastomosis changes its direction (Figure 3 a). Flow portions from the proximal as well as the distal vein travel back to the dialysis needle. The dye injected through the thin needle is drawn back into the single dialysis needle. Thus the SN mode causes a flow oscillation during the entire dialysis cycle just as it can be observed in the model arterial anastomosis of an AV fistula. As for the model arterial anastomosis, the backflow in the model AV graft is less pronounced than in the AV model due to the preset higher flow rate (600 ml/min vs. 350 ml/min, not shown).

4. AV graft, venous phase (Figure 3 b)

The expected flow patterns occur as described in the literature (stagnation point at the model venous wall opposite the anastomosis, vortex in the venous anastomosis) [4].

DISCUSSION

Due to demographic trends and medical progress, the number of patients requiring renal replacement therapy has been increasing steadily. Longer survival on hemodialysis also means that we have to face more complex and challenging situations regarding life-sustaining access vessels.

If only small areas of preexisting AV fistulas are suitable for puncture, or fistulas have not matured properly [5,6], SN dialysis may still be possible. In order to facilitate successful puncturing and hemodialysis, Twiss used SN dialysis already in 1964 [7], as SN dialysis may allow for the extended use of a poor quality vascular accesses and prolong fistula life. SN has scarcely been used till recently, however, because it is supposed to be less efficient than conventional DN

dialysis[1]. Modern pump systems have improved SN dialysis efficacy, though.

For SN dialysis, a substantial decrease in fistula flow during the arterial phase is characteristic. Conversely, an equivalent increase in flow occurs during the venous phase[8]. As these two distinct phases keep repeating with SN dialysis, a dialysis access is submitted to considerable repetitive hemodynamic changes during each dialysis session. In our experiments we could show that a significant reversal of the flow occurs during the arterial phase both in simulated AV-fistulas and AV-grafts. Subintimal hyperplasia within or near the anastomosis is a common cause for stenosis and for occlusion of the vascular access. Disturbances of flow patterns such as flow oscillations and abnormal wall shear stress cause vascular endothelial cells to change their orientations and shapes during each dialysis cycle[9~13]. These cell changes and the resulting intercellular gaps lead to interactions between blood components and the subendothelium. There subintimal hyperplasia usually starts eventually forming stenoses and leading to unwanted flow reduction or even vascular access occlusions. In addition, the retrograde flow in the distal artery during late diastole may cause steal phenomena in the poorly perfused distal extremity with ensuing symptomatic peripheral ischemia including pain, neurological symptoms, or even necroses. Low flow rates of an AV access lead to even more pronounced adverse effects of SN dialysis. For the reasons mentioned above SN dialysis should be avoided especially in low flow situations unless there is really no place for DN punctures.

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