An experimental right atrium platform to assess recirculation in hemodialysis catheters

Heaton, CED; Espino, Daniel

DOI:
10.1142/S0219519424500271

Document Version
Peer reviewed version

Citation for published version (Harvard):
Heaton, CED & Espino, D 2024, 'An experimental right atrium platform to assess recirculation in hemodialysis catheters', *Journal of Mechanics in Medicine and Biology*. https://doi.org/10.1142/S0219519424500271

An experimental right atrium platform to assess recirculation in hemodialysis catheters

CED Heaton[1^*], DM Espino[1]

[1]Department of Mechanical Engineering, University of Birmingham, B15 2TT, UK

* Corresponding author:

Charles ED Heaton
Centre for Additive Manufacturing
Faculty of Engineering
University of Nottingham
NG7 2GX
Nottingham
UK

Tel: +44 (0) 7887 372768
Email: Charles.Heaton@nottingham.ac.uk

^now based at the University of Nottingham.

Abstract

Hemodialysis (HD) is a treatment supporting decreased kidney function, via a catheter inserted into the heart's Right Atrium (RA). Recirculation is a source of inefficiency for treatment, where blood is dialysed again due to poor catheter design. Lab-testing is still relatively unexplored, hence, a mechanical testing system was designed with the intention of providing a consistent and repeatable environment for testing HD catheters. System geometry was composed using a Computer-Aided Design (CAD) model of a heart, with the RA scaled to appropriate dimensions, and a PolyDiMethylSiloxane (PDMS) model produced through 3D printing and negative wax casting. Pulsatile blood flow was mimicked by peristaltic pumps driving a blood analogue (BA). Recirculation was induced by adding dyed BA to the system via the catheter and measured using a colourimeter. The developed platform was initially evaluated using two catheters, demonstrating capability to accurately replicate atrial hemodynamic conditions. Two step-tipped catheters, A and B, were tested at 350 ml/min, producing recirculation values of 13.11% and 18.58%, respectively. The results exhibit the ability of the system developed to evaluate HD catheter performance, with potential to explore a wider range of tip geometries relevant to clinical preference. Furthermore, this advancement towards an anatomically accurate lab-based test system could be paired with computational methods to progress the evaluation of such medical devices and enhance their development.

Keywords

Additive manufacture, Catheter, Hemodialysis, Recirculation, Right Atrium, 3D printing

Introduction

In the UK, over 26,000[1] people require Hemodialysis (HD) treatment, which involves 15 hours of therapy weekly, thus, treatment efficiency and effectiveness are important to a patient's quality of life. HD is a process where blood is removed from the body, filtered of waste materials and excess fluids through a dialysis machine, and returned. This process is carried out via several modalities, with HD catheters being the most prevalent, but least favourable.[2–4] This involves a catheter being

inserted via a large central vein, with the tip resting in the top of the Right Atrium (RA) of the heart.[5] This situates the catheter in a turbulent, everchanging environment, with pulsatile blood flow coming into the atrium from the superior and inferior directions by the Superior Vena Cava (SVC) and Inferior Vena Cava (IVC).

Problematic recirculation[6] occurs when already filtered blood re-enters the catheter and is filtered again, causing inefficiency. This primarily occurs when the catheter is operated in reversed flow to clear thrombotic occlusions.[7,8] Tip design is critical in minimising this phenomenon, which comes in three varieties; step, split and symmetrical, with none displaying clear efficacy despite attempts to investigate performance in a manner of ways.[9] Clinical trials provide true *in vivo* performance, however, cannot offset the high inconsistency of catheter conditions from patient-to-patient and clinical staff variability.[10,11] Physical test-systems fall short regarding system geometry and appropriate placement for the functional tip of the catheter. Existing work oversimplifies system geometry, locating the catheter in a cylindrical tube representing the SVC, whereas appropriate placement should include the RA.[12,13]

Computational Fluid Dynamics (CFD) modelling has identified the benefits of anatomical accuracy. Owen et al.[14] investigated tip performance in a cylindrical SVC model with laminar flow (Figure 1.a,b), contrary to recommended catheter placement from advisory bodies (KDOQI)[3] and current studies[12,13] where RA positioning is preferable. Oliveira et al.[15] anatomically modelled the RA, providing an environment with more suitable flow conditions and catheter placement (Figure 1.c,d).

Geometrical accuracy could be applied to lab testing methods. Whilst CFD offers high analytical capability, physical testing is required to validate findings. Moreover, regulatory bodies, such as the FDA exhibit the need for such a system for clinical clearance.[3,16]

The aim of this study was to design and commission an experimental system to mimic *in vivo* conditions within the right atrium, providing a repeatable method of assessing recirculation through hemodialysis catheters. The apparatus has been commissioned by evaluating the performance of two

catheters, which would enable the testing of a broader variety of devices, varying by geometry and design features in future.

Methodology

System Overview

Figure 2.a details the proposed system to deliver these requirements, via flow directions, pump and sensors. Dialysis machines use peristaltic pumps, making them a suitable option to provide catheter function[3,17], and deliver pulsatile flow to the blood vessels. Pressure sensors in each line provided feedback, aiming to keep conditions within the RA below 10 mmHg[18], and ideally between 2-6 mmHg.[19] An aqueous glycerine mixture was used to mimic the viscosity of blood.

Right Atrium Geometry

A 3D model of a complete cadaveric human heart was downloaded from Thingiverse[20] and modelled in Solidworks (2021, Dassault Systèmes, Vélizy-Villacoublay, France) (Figure 3.a). The RA was isolated with an atrial chamber generated, and resized to a volume of 123 ml (Figure 3.b). Resizing compensated for post-mortem shrinkage.[21] The volume of the resultant model is within maximal ranges determined by short-axis (SA) and area-length (AL) methods, 101.0 ± 30.2 ml and 103.2 ± 32.6 ml respectively.[22,23] The SVC superiorly and IVC inferiorly converge in the RA, with blood exiting via the TV. These structures were resized to fit the expected dimensions (Table 1), with information regarding the respective studies accessible in supplementary table S1.[22–28]

Table 1: Modelled dimensions (major and minor axis dimensions have been taken to for features of high irregularity).

Anatomy	Model Dimensions
RA Volume	123 ml
SVC Diameter	18 mm
IVC Diameter	18 mm
TV Diameter	Major axis: 31.5 mm Minor axis: 25.8 mm

A 4-part mould was generated in CAD, then 3D printed out of a rigidRGD720 (Figure 3.c-e) using an Objet30™Prime printer. A wax casting was taken of the atrial volume (Figure 3.f-g).

The wax model was set in PolyDiMethylSiloxane (PDMS), its optical clarity, easy setting procedure, and flexibility make it appropriate for this application.[29] SYLGARD™ 184 (Dow, Midland, US) was used at a 10:1 ratio of silicone base to curing agent. Degassing occurred in a Lab Companion Vacuum Desiccator (Thermo Fisher Scientific, Waltham, US), (Figure 4.a). PDMS was left to cure at room temperature for five days. The PDMS was then withdrawn from the container, excess material removed and access made to the blood vessels to allow molten wax out. The whole model was then placed in a TO2020 oven (Severin Elecktro, Germany) at 100°C for one hour to melt the wax (Figure 4.c).

Blood Analogue

To match the dynamic viscosity of blood, an aqueous glycerine (Biorigins, São Paulo, Brazil) was prepared at a ratio of 46:54 glycerine-to-water.[30] This gave the BA a dynamic viscosity of 4.3±0.03 cP, which sits within 2% of the physiological target of 4.4±0.5 cP.[31] Other studies suggest blood viscosity is in the range of 3.5-5.5 cP with a mean of approximately 4.7 cP.[32,33]

Recirculation Measurement and Colorimetry

The venous BA was dyed blue at a known concentration, to measure dye presence in the fluid withdrawn by the catheter. Allowing magnitude of recirculation to be determined using adaptations of dilution formula. A PasPort colorimeter (Pasco, Roseville, US) was used to measure the dye transmittance and absorbance in the BA. Prior to usage, these parameters were mapped over a range of known concentrations with the Blue Dye (Convenient Drain & Pipe Solutions Ltd, Birmingham, UK).

Samples where transmittance and absorbance are either at maximum or minimum values, were discarded because it is indeterminable when the concentration, C, achieves these conditions. Matlab's Curve Fitting Toolbox (R2021b, Natick, US) was used to generate polynomial equations (Equation 1), governing concentration in the range: $0<C<10$ g/L. Coefficients for each are shown in table 2, with plots available in the supplementary material.

$$C = p_1x^3 + p_2x^2 + p_3x + p_4$$ Eq. 1

Table 2: Coefficients and goodness of fit for concentration polynomial equations.

Parameter	p_1	p_2	p_3	p_4	R^2
Transmittance	-23.38	46.65	-33.36	9.987	0.9885
Absorbance	-0.2068	0.802	7.245	0.22	0.9983

A mean was taken of transmittance and absorbance results to equation 1, to be used in determining the dye concentration of BA withdrawn by the catheter. Thus allowing for recirculation to be calculated (Eq.2).

$$R = \frac{C_{venous}}{C_{arterial}}$$ *Eq. 2*

Where R is recirculation (%) and C is concentration (g/L)

System Calibration and Assembly

The pressure sensing system was calibrated using hand calculations for a visual output in terms of $mmHg^{-1}$. Two types of peristaltic pumps were included in the system. A G928 (Garosa) pump provided the catheter function, and a Schlauchpumpe HP1100 (GTTechnik) supplied the blood flow. All components were connected together, centring on the PDMS block, which in turn was suspended between two clamp stands to be in an anatomically appropriate orientation (Figure 5).

Devices were incorporated into the testing platform via attachment to standard Luer lock connections which are used consistently across manufacturers. This permits for the evaluation of any catheter fitted with these standardised connectors.

Commissioning

Two catheters, named catheter A and catheter B for this purpose, were supplied by Kimal Plc to commission the test apparatus (Table 3). Both were 14 Fr (4.67 mm dia.) as this is a common choice for appropriate flow rate.[34] Catheter A was a step-tipped catheter with no additional geometry. Catheter B was a step-tipped catheter featuring an array of side holes.

Table 3: Specifications for catheters being tested.

Catheter	French size (dia.)	Tip Variety	Notable features	Tip Design
A	14	Step	No side holes or additional geometry	
B	14	Step	Circular and ovular side holes	 

Preliminary Setup

BA was mixed and distributed between the venous catheter line tank and blood supply tanks proportionately. The venous tank had dye added at a concentration of 10 g/L, with colourimeter readings taken and recorded. The Power Supply Units (PSUs) were set to deliver the voltage requirements for each pump, enabling the required flow (Table 4). Whilst 300 ml/min is the recommended minimum flow advised by advisory bodies[3], 350 ml/min was selected as being more representative of clinical practice.[35,36] Calibration data for the dye mapping, pressure sensor calibration and pump calibration are provided as supplementary data (figures S1 to S3.)

Table 4: Pump PSU requirements.

Line (pump)	Desired Flow Rate, Q (ml/min)
Catheter (G928)	350
Blood vessels (HP1100)	2000

Testing Procedure

Blood vessel pumps were run initially until RA submersion occurred, after which the GP28 pumps were activated. The system was then run for 30 s, at which point all pumps were switched off and the

timer stopped. Colourimeter readings were taken of the arterial tank with recirculation calculated (Equations 1 and 2); a procedure repeated three times per catheter.

Ethical approval: an advantage of this study being *in vitro* is that it did not involve human participants, patient studies/data or animal test subjects. Approval for the study was granted via the University of Birmingham's School of Engineering U/G-research project panel.

Results

Measurements of the dye transmittance and absorbance were taken 3 times for each catheter, Table 5. This allowed for the calculation of the dye concentration in the atrial BA using initial values for the venous BA (T = 2.70, A = 1.56; C = 8.95 g/L) and consequently the recirculation.

Table 5: Colourimetry data for catheters A and B from experimental stage.

Catheter	Transmittance (%)			Absorbance			Atrial BA dye concentration (g/L)		
	1	2	3	1	2	3	1	2	3
A	74.4	83.6	73.8	0.1	0.078	0.132	1.21	0.91	1.27
B	71.1	64.2	51.4	0.102	0.192	0.294	1.20	1.60	2.13

Catheters A and B showed mean recirculation of 13.11% and 18.58%, respectively. Catheter A had a lower mean recirculation by 5.46%. The SD values are low compared to the data range, suggesting repeatable testing.

Table 6: Recirculation results, mean and SD for catheters A and B.

Catheter	Recirculation, R (%)				
	1	2	3	Mean ($\bar{R}$)	SD
A	13.93	11.22	14.18	13.11	1.64
B	15.29	17.82	22.62	18.58	3.73

Discussion

A system was manufactured to evaluate hemodialysis catheter performance, with distinct efforts towards anatomical accuracy with geometry sourced from a CT scan and appropriately resized. Dye tracing provided means for determination of catheter induced recirculation, and thus delivering quantifiable system outputs. Two step-tipped catheters were tested to commission the setup.

Two step-tipped catheters were selected to exemplify the platforms capability to assess catheter recirculation, with the chosen devices possessing differing geometry in terms of side hole features. This would allow the system's ability to exhibit an expected performance difference between the catheters. Furthermore, a selected CFD study,[14,15] where the geometry and location of side holes was investigated, is used to validate the expected outcomes of the two devices. The aforementioned study suggests that catheter B would induce higher recirculation due to the specific location of its side holes, residing directly in the inflow path when in reversed operation. The side hole in question, is located closest to the tip of catheter B, which, when acting in reverse, will be withdrawing BA from the system. Thus, when the 'filtered' blood enters through the alternate lumen, it will pass directly over this opening and is promptly withdrawn from the system. This demonstrates the ability to differentiate between devices of different geometry, and the ability to evaluate design features of a HD catheter, whilst performing in the expected manner. The use of computational-based literature in this work establishes a new model for device assessment; whereby a combined computational-experimental practice could be put in place, offering a more reliable method to test catheters going forwards.

The recirculation values measured with our set-up are consistent with those from existing studies that include both *in vivo* and *in silico* approaches. A clinical study yielded recirculation rates between 18-24% for reversed flow configuration across 37 patients.[37] Whilst step-tipped catheters inserted into male pigs and operated in reversed flow displayed recirculation in the range of 18-30%.[38] Vesely et al measured recirculation in the range of 15-20% for step-tip catheters.[39] The previous work displayed broadly agrees with the findings of this study (mean: 13.11% (A), 18.58% (B)), with particular focus on the *in silico* method.

The principal advantage offered by our methodology is the improvement in anatomical accuracy through the use of an heart model replicate the RA. This enabled placing within the RA rather than a cylindrical tube representing the SVC. Furthermore, SVC placement leads to conservative

recirculation results, opposed to the RA where turbulence and stagnating flow increase recirculation likelihood.[12,13,40] Thus, this experimental approach shows the benefit of anatomical modelling.

Cylindrical models cannot produce turbulent conditions of the RA, with a laminar flow passing around the catheter. This is not conducive to provide realistic conditions for recirculation to occur, due to the dialysed blood being withdrawn from the proximity of the catheter too early. Instead, anatomical modelling[15] provides the turbulence and stagnation necessary to enable recirculation, whilst also offering the option to investigate catheter tip placement.

The FDA and the Medical Device Innovation Consortium (MDIC) noted the need to improve the regulatory system particularly in terms of delivering new devices using computer modelling and simulations.[41] Physical testing should be used as the final stage in device development, as validation of the computational phase and final confirmation of device performance with consideration to regulatory frameworks.

Modelling the RA used studies of both a broad age range and gender-divide, with no specific demographic was targeted. The intention was to provide an improvement on current lab-testing for industry usage; in future, a patient-specific approach might prove beneficial, however, at present this is not standard clinical practice. The techniques involved in scaling the CAD model demonstrates the potential to create a range of geometries, representative varying anatomical dimensions.

Limitations

The proposed experimental apparatus can be used to consider a broader range of experimental variables, such as BA rheology, system flow rate, to improve the modelled accuracy of the RA simulator. Anatomical flow rates (5 L/min) would be valuable to evaluate,[42,43] this however, does not prevent the system from demonstrating its provision of an anatomically accurate flow environment for recirculation measurement. Whilst it is accepted that difference in flow rates would not cause variation between recirculation due to the used Newtonian fluid, this does highlight a further

limitation, whereby the physical modelling of non-Newtonian fluid is inherently difficult. In terms of flow modelling, a functional tricuspid valve, perhaps fabricated from a polyurethane membrane, could be considered. Potential revisions would also direct attention towards the of dye mapping process, where it is acknowledged that a log-linearisation strategy could be applied using the Beer-Lambert law.

This study used two step-tipped catheters with differing side-hole geometries to demonstrate the ability to evaluate device performance. It is acknowledged that in a clinical setting a wider range of tip varieties might be considered, such as split or symmetrical.[44] When acknowledging catheters of differing variety, one significant model for evaluation would be the Palindrome symmetrical tipped.[45,46] This would provide a useful benchmark due to its existing prevalence in literature, primarily focused on a clinical setting. Nevertheless, the comparison of a stepped-tip and stepped-tip with side-holes, used in our study, has demonstrated a measurable difference in recirculation (of around 5%); highlighting the ability of the proposed testing apparatus to measure function changes in HD tip designs due to design features.

Consequently, future work would consider the evaluation of a wider range of devices to allow informed decisions regarding catheter performance. However, the aim of this study was to evidence the ability of the proposed experimental platform to assess HD catheters within realistic RA geometry and flow conditions, which has been achieved. The proposed system would be valuable to the aid of device development by directly testing its efficacy and recirculation, following preliminary evaluation through computational methods.

Conclusion

A functional RA model was developed and fabricated, providing a testing environment for HD catheters with realistic conditions, not seen in literature before. A CT scan was used to form an anatomically accurate PDMS replica of the RA, using 3D modelling, 3D printing and negative wax casting. Recirculation was the primary focus of this assessment due to its prevalence as an issue in

current dialysis treatment, assessed through the use of dye tracing. Areas for revision have been identified, but despite those, the initial system testing can be considered a success; analysing two devices and providing appropriate and consistent values for recirculation, supporting expectations about the catheters' performance difference. With benefit to be found in the novel approach to system design, replicating correct physical geometry and tip placement for HD catheters. Furthermore, the results of the preliminary testing display consistency with both comparative studies and clinical investigations.

Acknowledgements

The authors would like to thank Kimal Plc for funding experimental and consumable costs associated with this project, and Adam Sheward specifically for providing advice throughout.

The authors also thank the technical staff at the School of Engineering, University of Birmingham, for technical assistance with additive manufacture, specifically: Simon Payne-Rowan and Dr James Churm.

This work was completed at the School of Engineering, University of Birmingham. CED Heaton is now based at the University of Nottingham and is funded by an Engineering & Physical Sciences Research Council scholarship.

References

1. Mahase E. Covid-19: increasing demand for dialysis sparks fears of supply shortage. BMJ. 2020 Apr 21;369:m1588.

2. Bream PR. Update on Insertion and Complications of Central Venous Catheters for Hemodialysis. Semin Intervent Radiol. 2016 Mar 1;33(1):31–8.

3. Rocco M, Daugirdas JT, Depner TA, Inrig J, Mehrotra R, Rocco M V., et al. KDOQI Clinical Practice Guideline for Hemodialysis Adequacy: 2015 Update. American Journal of Kidney Diseases. 2015 Nov 1;66(5):884–930.

4. Byrne C, Caskey F, Castledine C, Davenport A, Dawnay A, Fraser S, et al. The UK Renal Registry. Nephron. 2018;139(1):1–12.

5. Smith RN, Nolan JP. Central venous catheters. Vol. 347, BMJ (Online). BMJ Publishing Group; 2013.

6. Kousoula V, Georgianos PI, Mavromatidis K, Syrganis C, Thodis E, Panagoutsos S, et al. Reversed connection of cuffed, tunneled, dual-lumen catheters with increased blood

flow rate maintains the adequacy of delivered dialysis despite the higher access recirculation. Int Urol Nephrol. 2019 Oct 1;51(10):1841–7.

7. Besarab A, Pandey R. Catheter management in hemodialysis patients: Delivering adequate flow. Vol. 6, Clinical Journal of the American Society of Nephrology. 2011. p. 227–34.

8. Moist LM, Hemmelgarn BR, Lok CE. Relationship between blood flow in central venous catheters and hemodialysis adequacy. Clin J Am Soc Nephrol. 2006;1(5):965–71.

9. Ling XC, Lu HP, Loh EW, Lin YK, Li YS, Lin CH, et al. A systematic review and meta-analysis of the comparison of performance among step-tip, split-tip, and symmetrical-tip hemodialysis catheters. Vol. 69, Journal of Vascular Surgery. Mosby Inc.; 2019. p. 1282–92.

10. McQuillan RF, Clark E, Zahirieh A, Cohen ER, Paparello JJ, Wayne DB, et al. Performance of temporary hemodialysis catheter insertion by nephrology fellows and attending nephrologists. Clinical Journal of the American Society of Nephrology. 2015 Oct 7;10(10):1767–72.

11. Fung V, Schmittdiel JA, Fireman B, Meer A, Thomas S, Smider N, et al. Meaningful Variation in Performance A Systematic Literature Review 140 | Selection Process Content Abstraction and Synthesis. Vol. 48, Medical Care •. 2010.

12. Tal M, Friedman T, Mojiban H. Dialysis Catheter Tip Placement: The Functional Tip. Endovascular Today. 2013;73–5.

13. Tawk S, Barakat E, Hammer F. A proposed simple and accurate technique for optimal long-term hemodialysis catheter tip placement. Vol. 102, Journal of the Belgian Society of Radiology. Ubiquity Press; 2018.

14. Owen DG, de Oliveira DC, Qian S, Green NC, Shepherd DET, Espino DM. Impact of side-hole geometry on the performance of hemodialysis catheter tips: A computational fluid dynamics assessment. PLoS One. 2020 Aug 1;15(8 August).

15. De Oliveira DC, Owen DG, Qian S, Green NC, Espino DM, Shepherd DET. Computational fluid dynamics of the right atrium: Assessment of modelling criteria for the evaluation of dialysis catheters. PLoS One. 2021 Feb 1;16(2 February).

16. U.S Food and Drug Administration. Implanted Blood Access Devices for Hemodialysis Guidance for Industry and Food and Drug Administration Staff. 2016. Available from: http://www.regulations.gov.

17. Institute of Electrical and Electronics Engineers. CINTI 2013 : 14th IEEE International Symposium on Computational Intelligence and Informatics : proceedings : 2013 November 19-21, Budapest. 2013.

18. CViL - Cardiovascular Imaging Lab. CARDIAC CYCLE. 2017. Available from: http://cvil.ucsd.edu/wp-content/uploads/2017/02/cardiac-cycle.pdf

19. Ragosta M, Kennedy J. Normal Waveforms, Artifacts, and Pitfalls. In: Textbook of Clinical Hemodialysis. 2018. p. 17–55.

20. Replicant Nexus. Real Heart - Thingiverse. 2017. Available from: https://www.thingiverse.com/thing:2287455

21. Shedge R, Krishan K, Warrier V, Kanchan T. Postmortem Changes. 2022.

22. Sievers B, Addo M, Breuckmann F, Barkhausen J, Erbel R. Reference Right Atrial Function Determined by Steady-State Free Precession Cardiovascular Magnetic Resonance. Journal of Cardiovascular Magnetic Resonance. 2007 Sep;9(5):807–14.

23. Maceira AM, Cosín-Sales J, Roughton M, Prasad SK, Pennell DJ. Reference right atrial dimensions and volume estimation by steady state free precession cardiovascular magnetic resonance. 2013.

24. Sonavane SK, Milner DM, Singh SP, Abdel Aal AK, Shahir KS, Chaturvedi A. Comprehensive imaging review of the superior vena cava. Vol. 35, Radiographics. Radiological Society of North America Inc.; 2015. p. 1873–92.

25. Mahlon MA, Yoon HC. CT Angiography of the Superior Vena Cava: Normative Values and Implications for Central Venous Catheter Position. Journal of Vascular and Interventional Radiology. 2007 Sep;18(9):1106–10.

26. Mookadam F, Warsame TA, Yang HS, Emani UR, Appleton CP, Raslan SF. Effect of positional changes on inferior vena cava size. European Journal of Echocardiography. 2011 Apr;12(4):322–5.

27. European Society of Cardiology. Anatomy of tricuspid valve. Available from: https://www.escardio.org/Education/Practice-Tools/EACVI-toolboxes/3D-Echo/anatomy-of-tricuspid-valve

28. Huttin O, Voilliot D, Mandry D, Venner C, Juillière Y, Selton-Suty C. All you need to know about the tricuspid valve: Tricuspid valve imaging and tricuspid regurgitation analysis. Vol. 109, Archives of Cardiovascular Diseases. Elsevier Masson SAS; 2016. p. 67–80.

29. Faustino V, Catarino SO, Lima R, Minas G. Biomedical microfluidic devices by using low-cost fabrication techniques: A review. J Biomech. 2016 Jul 26;49(11):2280–92.

30. Yousif MY, Holdsworth DW, Poepping TL. A blood-mimicking fluid for particle image velocimetry with silicone vascular models. Exp Fluids. 2011 Mar;50(3):769–74.

31. Galduróz JCF, Antunes HK, Santos RF. Gender- and age-related variations in blood viscosity in normal volunteers: A study of the effects of extract of Allium sativum and Ginkgo biloba. Phytomedicine. 2007 Aug 6;14(7–8):447–51.

32. Nader E, Skinner S, Romana M, Fort R, Lemonne N, Guillot N, et al. Blood Rheology: Key Parameters, Impact on Blood Flow, Role in Sickle Cell Disease and Effects of Exercise. Front Physiol. 2019 Oct 17;10.

33. Chatpun S, Cabrales P. Effects of plasma viscosity modulation on cardiac function during moderate hemodilution. Asian J Transfus Sci. 2010;4(2):102.

34. Schwab SJ, Beathard G. The hemodialysis catheter conundrum: Hate living with them, but can't live without them. Vol. 56, PERSPECTIVES IN RENAL MEDICINE. 1999.

35. Vesely T. The challenges of Hemodialysis catheter use. Endovascular Today. 2013;60–1.

36. Agarwal AK, Ash SR, Akram AM, Anil A, Aslam P, Tung H, et al. Maintenance of blood flow rate on dialysis with self-centering CentrosFLO catheter: A multicenter prospective study. Hemodialysis International. 2016 Oct 1;20(4):501–9.

37. Senécal L, Saint-Sauveur E, Leblanc M. Blood Flow and Recirculation Rates in Tunneled Hemodialysis Catheters. ASAIO Journal. 2004 Jan;50(1):94–7.

38. Tal MG. Comparison of Recirculation Percentage of the Palindrome Catheter and Standard Hemodialysis Catheters in a Swine Model. Journal of Vascular and Interventional Radiology. 2005 Sep;16(9):1237–40.

39. Vesely TM, Ravenscroft A. Hemodialysis catheter tip design: Observations on fluid flow and recirculation. Journal of Vascular Access. 2016 Jan 1;17(1):29–39.

40. Dewhurst P, Coats L, Parikh JD, Hollingsworth KG, Gan L. The role of flow rotation in the adult right atrium: A 4D flow cardiovascular magnetic resonance study. Physiol Meas. 2020 Mar 1;41(3).

41. Faris O, Shuren J. An FDA Viewpoint on Unique Considerations for Medical-Device Clinical Trials. New England Journal of Medicine. 2017 Apr 6;376(14):1350–7.

42. Rodríguez AO. Quantification of Vena Cava Blood Flow with Half Fourier Echo-Planar Imaging. Arch Med Res. 2002 Mar;33(2):167–74.

43. Cheng CP, Herfkens RJ, Taylor CA. Inferior vena caval hemodynamics quantified in vivo at rest and during cycling exercise using magnetic resonance imaging. American Journal of Physiology-Heart and Circulatory Physiology. 2003 Apr 1;284(4):H1161–7.

44. Ling XC, Lu HP, Loh EW, Lin YK, Li YS, Lin CH, et al. A systematic review and meta-analysis of the comparison of performance among step-tip, split-tip, and symmetrical-tip hemodialysis catheters. J Vasc Surg. 2019 Apr;69(4):1282–92.

45. Jonczyk M, Althoff C, Slowinski T, Lieker I, Naik M, Auer J, et al. Urea-based recirculation validation of the symmetrical palindrome catheter. J Ren Care. 2017 Dec 16;43(4):242–6.

46. Nadolski GJ, Redmond J, Shin B, Shamimi-Noori S, Vance A, Hammelman B, et al. Comparison of Clinical Performance of VectorFlow and Palindrome Symmetric-Tip Dialysis Catheters: A Multicenter, Randomized Trial. Journal of Vascular and Interventional Radiology. 2020 Jul;31(7):1148–55.

Figure Captions

Figure 1: Differing CFD setups: a,b) SVC, would result in laminar flow [18] reproduced from "Impact of side-hole geometry on the performance of hemodialysis catheter tips: A computational fluid dynamics assessment" licenced under CC BY 4.0; c,d) RA geometry showing turbulent flow with correct placement [19] reproduced from "Computational fluid dynamics of the right atrium: Assessment of modelling criteria for the evaluation of dialysis catheters" licenced under CC BY 4.0.

Figure 2: (a) Schematic of system architecture; (b) Right Atrium fluid volume with optimal catheter placement

Figure 3: RA model development: (a) Whole heart CAD model from Thingiverse; (b) RA fluid volume CAD model; (c,d) Mould parts generated from fluid volume for 3D printing in SolidWorks; (e) RGD720 3D printed mould parts; (f,g) Soy wax casting.

Figure 4: PDMS setting process (a) Positioning the wax model in the PDMS mix with weighted cups to ensure model submersion; (b) Cured PDMS removed from container;(c) final PDMS setting with wax removed and excess PDMS trimmed from edges.

Figure 5: System assembled and suspended by clamp stands, in operation, i) SVC inlet from pump; ii) venting tube; iii) catheter connected into system and to bloodlines; iv) IVC inlet from pump; v) ball valve; vi) outlet tube, raised above RA chamber to aid submersion; vii) catheter pressure sensors to Elegoo; viii) waste, arterial and venous tanks.

Figure 6: Bar chart displaying recirculation samples for each catheter.