13. Litwak KN, Koenig SC, Tsukui H, Kihara S, Wu Z, Pantalos GM. Effects of left ventricular assist device support and outflow graft location upon aortic blood flow. *ASAIO J*. 2004;50:432-7.
14. Karmonik C, Partovi S, Loebe M, Schmack B, Weymann A, Lumsden AB, et al. Computational fluid dynamics in patients with continuous-flow left ventricular assist device support show hemodynamic alterations in the ascending aorta. *J Thorac Cardiovasc Surg*. 2014;147:1326-33.e1.
15. Laumen M, Kaufmann T, Timms D, Schlanstein P, Jansen S, Gregory S, et al. Flow analysis of ventricular assist device inflow and outflow cannula positioning using a naturally shaped ventricle and aortic branch. *Artif Organs*. 2010;34:798-806.
16. Kaufmann TA, Hormes M, Laumen M, Timms DL, Schmitz-Rode T, Moritz A, et al. Flow distribution during cardiopulmonary bypass in dependency on the outflow cannula positioning. *Artif Organs*. 2009;33:988-92.
17. Kar B, Delgado RM 3rd, Frazier OH, Gregoric ID, Harting MT, Wadia Y, et al. The effect of LVAD aortic outflow-graft placement on hemodynamics and flow: implantation technique and computer flow modeling. *Tex Heart Inst J*. 2005;32:294-8.
18. May-Newman K, Hillen B, Dembitsky W. Effect of left ventricular assist device outflow conduit anastomosis location on flow patterns in the native aorta. *ASAIO J*. 2006;52:132-9.
19. Markl M, Benk C, Klausmann D, Stalder AF, Frydrychowicz A, Hennig J, et al. Three-dimensional magnetic resonance flow analysis in a ventricular assist device. *J Thorac Cardiovasc Surg*. 2007;134:1471-6.
20. Benk C, Lorenz R, Beyersdorf F, Bock J, Klemm R, Korvink JG, et al. Three-dimensional flow characteristics in ventricular assist devices: impact of valve design and operating conditions. *J Thorac Cardiovasc Surg*. 2011;142:1019-26.
21. Lorenz R, Benk C, Bock J, Stalder AF, Korvink JG, Hennig J, et al. Closed circuit MR compatible pulsatile pump system using a ventricular assist device and pressure control unit. *Magn Reson Med*. 2012;67:258-68.
22. Benk C, Mauch A, Beyersdorf F, Klemm R, Russe M, Blanke P, et al. Effect of cannula position in the thoracic aorta with continuous left ventricular support: four-dimensional flow-sensitive magnetic resonance imaging in an in vitro model. *Eur J Cardiothorac Surg*. 2013;44:551-8.
23. Klotz S, Meyns B, Simon A, Wittwer T, Rahmanian P, Schlensak C, et al. Partial mechanical long-term support with the CircuLite Synergy pump as bridge-to-transplant in congestive heart failure. *Thorac Cardiovasc Surg* 2010;58 Suppl 2:S173-8.
24. Meyns B, Klotz S, Simon A, Droogne W, Rega F, Griffith B, et al. Proof of concept: hemodynamic response to long-term partial ventricular support with the synergy pocket micro-pump. *J Am Coll Cardiol*. 2009;54:79-86.
25. Meyns BP, Simon A, Klotz S, Wittwer T, Schlensak C, Rega F, et al. Clinical benefits of partial circulatory support in New York Heart Association Class IIIB and Early Class IV patients. *Eur J Cardiothorac Surg*. 2011;39:693-8.
26. Fresiello L, Zieliński K, Jacobs S, Di Molfetta A, Palko KJ, Bernini F, et al. Reproduction of continuous flow left ventricular assist device experimental data by means of a hybrid cardiovascular model with baroreflex control. *Artif Organs*. 2014;38:456-68.
27. Barbone A, Pini D, Rega F, Ornaghi D, Vitali E, Meyns B. Circulatory support in elderly chronic heart failure patients using the CircuLite Synergy system. *Eur J Cardiothorac Surg*. 2013;44:207-12.
28. Sabashnikov A, Popov AF, Bowles CT, Mohite PN, Weymann A, Hards R, et al. Outcomes after implantation of partial-support left ventricular assist devices in inotropic-dependent patients: Do we still need full-support assist devices? *J Thorac Cardiovasc Surg*. 2014;148:1115-21.

Key Words: aortic hemodynamics, 4D flow MRI, LVAD, outflow graft

EDITORIAL COMMENTARY

Adding a new dimension to our understanding of continuous-flow physiology

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See related article on pages 200-7.

In the United States from 2006 through 2013, approximately 10,000 continuous-flow left ventricular assist devices (CF-VADs) were implanted. Data from the Interagency Registry for Mechanical Circulatory Support showed a 1-year

mortality in patients bridged to transplant of only 12%, and these results have led to the proposal that CF-VADs be considered as an alternative to transplantation.^{1,2} Despite this large clinical experience and these outstanding results, our understanding of the physiology of CF-VADs is extremely limited. As an example, it is very difficult to measure low-pulsatility blood pressure, and the safest long-term level of “mean” blood pressure is unknown.

In this issue of the *Journal*, Jung and colleagues³ from the University Hospital Bern report their elegant use of 4-dimensional flow-sensitive magnetic resonance imaging to assess the impact of a CF-VAD on the flow characteristics in a mock circulation of the thoracic aorta and extracranial cerebral vessels. They and their reviewers note some of the limitations, including the use of a pulsatile device as the heart, the fixed uniform resistance across multiple arteries,

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wall compliance that likely differs from human vessels, and the use of the subclavian artery for inflow (although this last is increasingly common with less invasive approaches⁴).

Jung and colleagues³ concluded that “no drastic consequences on the flow characteristics in the aorta could be observed.” When, however, the results are examined for insight into the some of the vexing complications of CF-VADs, such as hemorrhagic strokes, gastrointestinal bleeding, and aortic regurgitation, things begin to look interesting.

In the moderately reduced cardiac function model, the cerebral blood in both carotids increased by 50% with respect to baseline as CF-VAD flow increased, but the right carotid flow was continuous while the left carotid flow was pulsatile. Cerebral autoregulation may be challenged by the need to manage distinctly different forms of cerebral blood flow.

The descending thoracic aortic flow was increased above baseline under all conditions. If it has reduced pulsatility, which is hypothesized as a possible etiology of intestinal angiodysplasia, could it be that low-pulsatility hyperemia explains the frequent gastrointestinal bleeding seen in patients?

Finally, Figure 3 in the article of Jung and colleagues³ displays some interesting flow vortices, which in the standard placement of the outflow graft to the ascending aorta would form right above the aortic valve. Jung and colleagues³ “assume these do not play a significant role with

respect to valve dysfunction,” but could these vortices place abnormal stresses on the intermittently opening aortic valve? If inflow is from the subclavian artery, will there be vortices at the base of the aortic arch vessels, and could they disrupt atheromatous material?

Much of what I have suggested is speculation, and as with any innovative original research the findings will need confirmation and have generated more questions than answers. It is this type of work that adds a much needed new dimension to our understanding of the fundamental alterations in physiology with continuous-flow mechanical support.

References

1. Kirklin JK, Naftel DC, Kormos RL, Pagani FD, Myers SL, Stevenson LW, et al. Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS) analysis of pump thrombosis in the HeartMate II left ventricular assist device. *J Heart Lung Transplant*. 2014;33:12-22.
2. Kirklin JK, Naftel DC, Pagani FD, Kormos RL, Stevenson L, Miller M, et al. Long-term mechanical circulatory support (destination therapy): on track to complete with heart transplantation? *J Thorac Cardiovasc Surg*. 2012;144:584-603; discussion 597-8.
3. Jung B, Müller C, Buchenberg W, Ith M, Reineke D, Beyersdorf F, Benk C. Investigation of hemodynamics in an in vitro system simulating left ventricular support through the right subclavian artery using 4-dimensional flow magnetic resonance imaging. *J Thorac Cardiovasc Surg*. 2015;150:200-7.
4. Maltais S, Danter MR, Haglund NA, Schmitto JD, Stulak JM. Nonsternotomy approaches for left ventricular assist device placement. *Oper Tech Thorac Cardiovasc Surg*. 2014;19:276-91.