The steam locomotive makes a comeback: A new solution to staged single-ventricle palliation?

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Achieving long-term survival and good quality of life for patients with single-ventricle circulations remains one of the greatest challenges in the field of congenital heart disease. Much of the mortality occurs during the period of "shunt dependency." The concept of avoiding this period by allowing the bidirectional Glenn shunt to be performed during the neonatal period has always been appealing, but attempts to do so have been unsuccessful.

In the current issue of the *Journal*, Esmaily-Moghadam and coworkers¹ propose to combine the bidirectional Glenn shunt and placement of a restrictive systemic-to-pulmonary shunt during the stage 1 operation. On the surface, this idea seems counterproductive, as it would only serve to further raise superior vena caval (SVC) pressure, with its attendant risks in the neonatal period.

Esmaily-Moghadam and coworkers' approach, however, is more sophisticated than that. They seek to turn the shunt into a forward-directed, high-velocity jet that adds energy and momentum to the Glenn flow *without* a significant rise in SVC pressure. The mechanism is called the *ejector jet*. The phenomenon was instrumental in the design of the steam locomotive and has had widespread industrial applications.

To understand the ejector jet, consider Figure 1.² Two fluid compartments (*a* and *b*) are connected by a pipe of area A_2 . If the pressure in *a* (P_A) is greater than the pressure in *b* (P_B), the fluid flows left to right. In turn, imagine that fluid in compartment *b* must empty at a certain rate (Q) through a resistive orifice into a reservoir. This flow rate must be maintained by sufficiently large P_B . Whatever P_B is, P_A must be even greater without the ejector jet.

Now enter the ejector jet. It is powered by a pump that draws a relatively small amount of fluid (density ρ , rate Q_j) from compartment *a* and ejects it at high velocity into

FIGURE 1. Two compartments (*a* and *b*) filled with fluid (density ρ) are connected by a pipe of cross-sectional area A_2 . The ejector jet is powered by a pump that draws a relatively small amount of fluid from compartment *a* and ejects it at high velocity (V_j) into the pipe at position 1 through a small orifice (area A_j). The total flow enters compartment *b* at position 2. P_A , Pressure in compartment *a*; P_B , pressure in compartment *b*; ΔP , difference in pressure between compartments. Reprinted with permission.²

the pipe through a small orifice of area A_j . The jet entrains and mixes with the surrounding flow and imparts kinetic energy and momentum to it. The energized flow enters compartment *b* and diffuses, converting its kinetic energy back into pressure. *The ejector jet augments P_B without a rise in P_A , so the flow through the resistive orifice increases without a rise in compartment *a* pressure.* In fact, the pressure gradient ($P_B - P_A$) can reverse, and P_A may even decrease. Under certain assumptions, one finds the following equation holds:

$$P_B - P_A \approx -(\rho/2)(Q/A_2)^2 + \rho Q_j^2 / A_2 A_j.$$

In a computational model, Esmaily-Moghadam and coworkers inserted a shunt from the innominate artery to the SVC, angled in the direction of SVC flow and narrowed at the distal end to produce a high-velocity jet. This is the ejector jet. The pump is the ventricle. They found that, relative to the baseline Glenn circulation, the ejector jet shunt augmented pulmonary blood flow by about 30% with negligible increase in ventricular volume load and an increase in SVC pressure by about 33% (2 mm) for low pulmonary resistance (PVR) and 40% (4 mm) for high PVR. They suggest that by further optimizing the configuration of the shunt they may be able to achieve pulmonary blood flow and SVC pressure acceptable in the neonatal period, allowing the Glenn shunt to be performed with the stage 1 palliation.

As Esmaily-Moghadam and coworkers admit, however, there are still problems in designing the perfect ejector jet and making it function in the neonate. In the industrial

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world, even the “optimal” ejector jet is typically inefficient—about 30% to 35%. It is very sensitive to configuration. With anatomic and surgical restrictions, the efficiency might be considerably less and manifest as excessive SVC pressure, defeating the original intent of the operation. Indeed, Esmaily-Moghadam and coworkers did not find a model that actually decreases Glenn (SVC) pressure. Furthermore, the mechanism must work under conditions of elevated PVR and large variations in PVR, which influence SVC pressure. Any sustained elevation in SVC pressure by more than about 15 mm Hg could jeopardize cerebral circulation during systemic hypotension, either directly or indirectly through cerebral edema, and might promote rapid venous collateralization leading to hypoxemia. These are major challenges.

There may be an equally appealing, if not more workable application of the ejector jet, that is, to the “failing Fontan.” One could conceive of twin jets, fed by either the aorta or the ventricle itself, inserted at the pulmonary-venous confluence and directed toward both lung hila. It can be demonstrated that this ejector jet could transfer energy to the Fontan with a shunt less than 1.5. Working in Alain

Kassab’s laboratory at the University of Central Florida, my colleagues and I have demonstrated an actual pressure decrease in the inflow (“venous”) compartment simultaneous with a flow increase in the outflow (“pulmonary”) of a schematic numeric model incorporating an ejector jet. We are now modeling this in a closed-loop multiscale model of the complete Fontan circulation.

The ejector jet is based on a fascinating fluid dynamical phenomenon. In the proposed applications, it taps the native energy of the heart and functions as a pump with no moving parts. In principle, it can be surgically placed and interventionally managed. The steam locomotive may make a comeback—on a very different track.

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