Four-dimensional flow magnetic resonance imaging demonstrates near normalization of aortic flow after the Ross procedure

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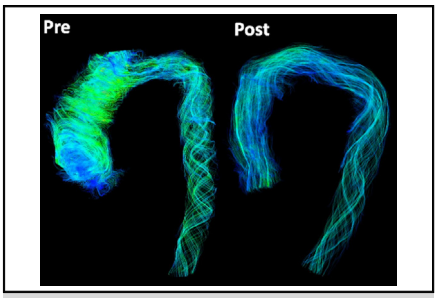


Preoperative and postoperative 4D-flow MRI in a patient undergoing the Ross procedure.

CENTRAL MESSAGE

4D-flow MRI provides a noninvasive method to evaluate preoperative blood flow in patients with aortic valve failure and resultant postoperative hemodynamic improvements following the Ross procedure.

Video clip is available online.

The Ross procedure was first described in 1967. In it, the diseased aortic valve is replaced with a pulmonary autograft and the pulmonary valve is replaced with a homograft.[1] Benefits of the Ross procedure include improved survival in patients younger than age 50 years, superior hemodynamics compared with manmade prostheses, and avoidance of lifetime anticoagulation therapy.[2] This procedure is experiencing a resurgence largely due to the demonstration of a survival benefit. Contemporary series have shown operative mortality on par with aortic valve replacement; however, up to 15% of Ross patients still experience autograft failure and the mechanisms of failure are incompletely understood.[3] In this pilot study, we used 4-dimensional (4D) flow magnetic resonance imaging (MRI) to better understand the hemodynamics before and after the Ross procedure.

METHODS

Following institutional review board approval (No.: 2016-1346; approved January 17, 2017) and after obtaining written consent for publication from participants, candidates for the Ross procedure underwent preoperative and postoperative noncontrast 4D-flow MRI imaging with phase contrast vastly-undersampled isotropic projection reconstruction. Resulting phase contrast angiograms were imported into Mimics (Materialise NV) where the aorta and left ventricle were segmented. The aortic mask was imported for flow analysis into Ensight (Ansys) where planes were placed at 5 locations (sinotubular junction, mid ascending aorta, distal ascending aorta, proximal descending aorta, and distal thoracic descending aorta). Quantitative metrics obtained included volumetric flow rate, kinetic energy, vorticity, and helicity. Path lines were generated for each aorta for visualization of the temporal evolution of blood flow. Preoperative and postoperative data were analyzed using a 2-tailed, paired, Student *t* test.

RESULTS

Six patients (2 men, 4 women), age range 24 to 54 years, undergoing the Ross procedure at a single institution underwent preoperative and postoperative 4D-flow MRI. The etiology of aortic valve failure was bicuspid aortic valve in 4 out of 6 patients. In 3 out of 6 patients, there was a concurrent ascending aortic aneurysm repaired at the time of surgery. Qualitative data demonstrated near normalization of flow compared with age-matched healthy controls in the postoperative cases (Figure 1 and Video 1). Quantitative data demonstrated significantly improved volumetric flow rates and significant reductions in kinetic energy within

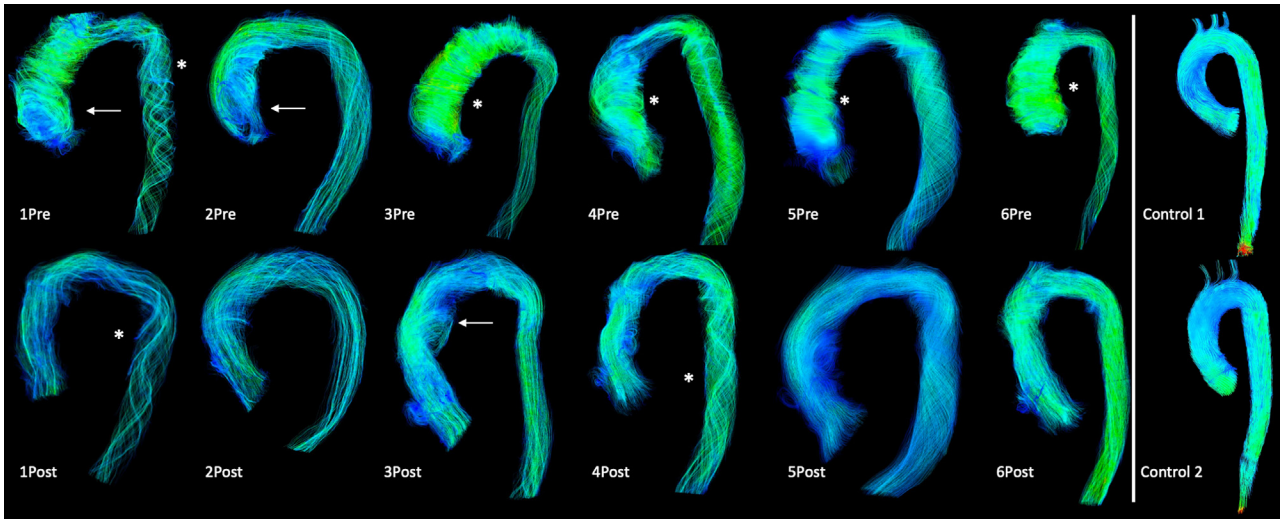


FIGURE 1. Qualitative images comparing patients before and after the Ross procedure with age-matched controls. Preoperative data are on the top row, postoperative data are on the bottom row. Control aortas are on the right. *Arrows* indicate abnormal vortical flow and *asterisks* indicate abnormal helical flow. The velocity scale is set to 1.5 m/second.

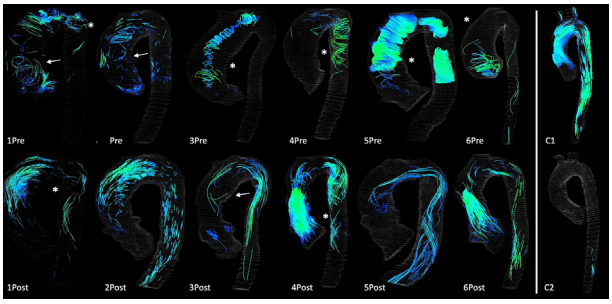
the aorta along with regional improvements in vorticity and helicity (Table 1).

DISCUSSION

The Ross procedure is a viable option for young patients with aortic valve disease because it improves survival and mitigates the need for lifelong anticoagulation therapy; however, some patients still experience Ross failure and require reintervention. The utilization of 4D-flow MRI to better understand cardiovascular hemodynamics is increasing; however, there are a lack of data with respect to the Ross procedure.

Previous studies compare the Ross procedure with other aortic valve replacement operations, but none compare flow preoperatively and postoperatively.[4,5] This pilot study demonstrates that patients undergoing the Ross procedure experience improvement in flow dynamics, as captured by 4D-flow MRI, thus offering a noninvasive method to evaluate these patients preoperatively and postoperatively, evaluate flow changes based on the surgical technique, and to follow changes in aortic hemodynamics over time. Namely, in this cohort, there were higher volumetric flow rates and reduced peak systolic kinetic energies in the ascending aorta. Furthermore, kinetic energy throughout the thoracic aorta was conserved postoperatively, whereas there was a steady decline in the preoperative group as flow moved distally. This is secondary to reductions in abnormal vortical and helical flow postoperatively that minimizes insensible energy losses. Of note, surgery did not completely normalize flow, as evidenced by some residual abnormal vortices and helices postoperatively but did greatly improve it.

There are several limitations of this study. First, this is a small, heterogeneous group of patients. A portion of these patients had a bicuspid aortic valve or underwent repair of an ascending aortic aneurysm at the time of the Ross procedure, complicating comparison of preoperative and postoperative groups. Next, these scans were not contrast-enhanced, which introduces greater sources of error with respect to any calculation that requires velocity.



VIDEO 1. Video version of Figure 1 comparing preoperative and postoperative Ross patients with age-matched controls. *Arrows* indicate abnormal vortical flow and asterisks indicate abnormal helical flow. The velocity scale is set to 1.5 m/second. Video available at: https://www.jtcvs.org/article/S2666-2507(24)00128-7/fulltext.

CONCLUSIONS

4D-flow MRI offers a noninvasive method to evaluate pre- and postoperative flow characteristics in patients undergoing the Ross procedure. Future studies will utilize 4D-flow MRI to follow these patients longitudinally to evaluate durability of the procedure over time and to compare the Ross procedure with mechanical aortic valve replacement.

TABLE 1. Quantitative data comparing preoperative and postoperative volumetric flow rates and peak systolic kinetic energies at predefined ascending aortic locations

	Location	Preoperative	Postoperative	*P* value
Peak systolic volumetric flow rate (mL/s)	Sinotubular junction	148.17 ± 204.09	238.93 ± 120.26	.069
	Mid ascending aorta	155.93 ± 141.56	289.21 ± 68.61	.004
	Distal ascending aorta	205.77 ± 115.09	262.48 ± 64.48	.049
	Proximal descending aorta	226.62 ± 66.89	194.23 ± 55.35	.075
	Distal descending aorta	192.13 ± 94.30	207.62 ± 41.81	.409
Peak systolic kinetic energy (J)	Sinotubular junction	1.73 ± 0.52	1.17 ± 0.33	.003
	Mid ascending aorta	1.55 ± 0.11	1.25 ± 0.15	.002
	Distal ascending aorta	1.48 ± 0.20	1.03 ± 0.13	<.001
	Proximal descending aorta	1.22 ± 0.08	1.13 ± 0.28	.123
	Distal descending aorta	1.09 ± 0.21	1.15 ± 0.32	.390
Peak systolic vorticity (m^2/s)	Sinotubular junction	1.06 ± 0.26	1.23 ± 0.20	.027
	Mid ascending aorta	1.27 ± 0.33	1.21 ± 0.24	.418
	Distal ascending aorta	1.18 ± 0.26	1.05 ± 0.16	.051
	Proximal descending aorta	1.21 ± 0.32	0.98 ± 0.08	.009
	Distal descending aorta	1.02 ± 0.25	1.10 ± 0.24	.225
Peak systolic helicity (m^3/s^2)	Sinotubular junction	0.57 ± 0.27	0.58 ± 0.18	.860
	Mid ascending aorta	0.83 ± 0.14	0.58 ± 0.17	.001
	Distal ascending aorta	0.69 ± 0.27	0.51 ± 0.22	.027
	Proximal descending aorta	0.47 ± 0.13	0.53 ± 0.13	.108
	Distal descending aorta	0.44 ± 0.17	0.43 ± 0.11	.779

Values are presented as mean ± SD.

Conflict of Interest Statement

The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

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