annuloplasty prosthesis alone would have been a better substrate for this study. Indeed, in healthy sheep implanted with annuloplasty rings only,⁹ the MRI flow patterns were substantially different from those presented herein.

The 4-dimensional MRI flow patterns reported in the presented patients offer a unique glimpse into the physiologic subtleties of degenerative mitral valve repair that goes beyond the usual gross assessment of valvular insufficiency. Other investigators¹⁰ have shown that even with successful restoration of valvular competence, the technical nuances of mitral repair may lead to distant morbidity. The current report adds impetus for further refinement of surgical technique. Advanced imaging techniques may be the new bellwether of not only competent but also physiologic mitral valve repair.

References

1. Hope MD, Hope TA, Crook SE, Ordovas KG, Urbania TH, Alley MT, et al. 4D flow CMR in assessment of valve-related ascending aortic disease. *JACC Cardiovasc Imaging*. 2011;4:781-7.
2. Fredriksson AG, Zajac J, Eriksson J, Dyverfeldt P, Bolger AF, Ebbers T, et al. 4-D blood flow in the human right ventricle. *Am J Physiol Heart Circ Physiol*. 2011;301:H2344-50.
3. Eriksson J, Bolger AF, Ebbers T, Carlhäll CJ. Assessment of left ventricular hemodynamic forces in healthy subjects and patients with dilated cardiomyopathy using 4D flow MRI. *Physiol Rep*. 2016;4(3).
4. Morichi H, Itatani K, Yamazaki S, Numata S, Nakaji K, Tamaki N, et al. Influences of mitral annuloplasty on left ventricular flow dynamics assessed with 3-dimensional cine phase-contrast flow magnetic resonance imaging. *J Thorac Cardiovasc Surg*. 2022;163:947-59.
5. Tsakiris AG, Gordon DA, Mathieu Y, Irving L. Motion of both mitral valve leaflets: a cinerentgenographic study in intact dogs. *J Appl Physiol*. 1975;39:359-66.
6. Timek T, Dagum P, Lai DT, Green GR, Glasson JR, Daughters GT, et al. The role of atrial contraction in mitral valve closure. *J Heart Valve Dis*. 2001;10:312-9.
7. Timek TA, Green GR, Tibayan FA, Lai DT, Rodriguez F, Liang D, et al. Aorto-mitral annular dynamics. *Ann Thorac Surg*. 2003;76:1944-50.
8. Dagum P, Timek T, Green GR, Daughters GT, Liang D, Ingels NB Jr, et al. Three-dimensional geometric comparison of partial and complete flexible mitral annuloplasty rings. *J Thorac Cardiovasc Surg*. 2001;122:665-73.
9. Witschey WR, Zhang D, Contijoch F, McGarvey JR, Lee M, Takebayashi S, et al. The influence of mitral annuloplasty on left ventricular flow dynamics. *Ann Thorac Surg*. 2015;100:114-21.
10. Ma W, Shi W, Wu W, Ye W, Kong Y, Zhu D, et al. Elevated gradient after mitral valve repair: the effect of surgical technique and relevance of postoperative atrial fibrillation. *J Thorac Cardiovasc Surg*. 2019;157:921-7.e3.

See Article page 947.

Check for updates

Commentary: Four-dimensional left ventricular flow imaging after surgical valve reconstruction—pretty pictures or marker of repair quality?

Dimosthenis Pandis, MD, and
Anelechi C. Anyanwu, MD, FRCS (Eng)

From Hippocrates and Vesalius to Ibn al-Nafis and William Harvey, the controversy of blood flow in medicine and philosophy has persisted for centuries. While

Abnormal blood flow dynamics in a patient with degenerative mitral valve disease.

CENTRAL MESSAGE

Ventricular flow dynamics are disrupted by mitral valve disease and its surgical treatment. The clinical and prognostic impact of disrupted flow dynamics is yet to be determined.

Leonardo DaVinci's description of vortex and laminar flow¹ should have bridged the chasm between rationalists and empiricists, it took 450 years before his hypotheses were corroborated in the laboratory by Brian Bellhouse and colleagues in Oxford in the 1960s, using dyes with

From the Department of Cardiovascular Surgery, Icahn School of Medicine at Mount Sinai, New York, NY.

Disclosures: The authors reported no conflicts of interest.

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

Received for publication May 28, 2020; revisions received June 1, 2020; accepted for publication June 2, 2020; available ahead of print June 24, 2020.

Address for reprints: Anelechi C. Anyanwu, MD, FRCS (Eng), Department of Cardiovascular Surgery, Icahn School of Medicine at Mount Sinai, 1190 Fifth Ave, Box 1028, New York, NY 10128 (E-mail: Anelechi.anyanwu@mountsinai.org).

J Thorac Cardiovasc Surg 2022;163:962-3

0022-5223/\$36.00

Copyright © 2020 by The American Association for Thoracic Surgery

<http://dx.doi.org/10.1016/j.jtcvs.2020.06.014>

FIGURE 1. Altered mitral leaflet geometry and LV remodeling are associated with abnormal intracavitary vorticity and increased kinetic energy dissipation which persist following surgical mitral repair. Computational flow models of a healthy subject and 2 case examples of degenerative mitral valve prolapse. *Upper panel:* altered blood flow vortex formation observed before (left) and following surgical mitral repair (right) in 2 case examples of chronic severe DMR versus a normal healthy subject. *Lower panel:* increased kinetic energy dissipation is observed in both patients with DMR (red and blue line – picture insert) at baseline (left) and following surgical mitral repair (right). Computational flow models generated in collaboration with Gianni Pedrizzetti, PhD, and Dario Colli, PhD, Department of Engineering and Architecture at the University of Trieste, Italy. NeoChord Repair: minimally invasive mitral valve repair of flail P2 segment via off-pump, transapical implantation of NeoChord artificial chordae (NeoChord Inc., Louis Park, Minn). MVR, Mitral valve repair; DMR, degenerative mitral regurgitation.

radiography to delineate blood flow patterns in the aortic root.² The subsequent momentum in hemodynamics³ was sustained by advancements in mapping blood particles' velocities using contrast echocardiography⁴ and magnetic resonance imaging.⁵ To summarize, as the trans-mitral inflow jet enters the left ventricular (LV) cavity, it interacts with 2 surface boundaries: the trailing mitral leaflet edges (promotes development of a shear layer), and the LV myocardium (rolls the apically-directed shear layer into a ring-shaped structure).⁶ Abnormal vortex formation and intracavitary hemodynamic forces are thus dependent on the synergistic role of changes in mitral leaflet geometry and LV deformation, itself contingent on the functional integrity of the working myocardium,⁷ resulting in altered hemodynamics and impaired myocardial performance.⁸

In the current issue of the *Journal*, Morichi and colleagues⁹ describe their observations of magnetic resonance imaging-derived LV and ascending aorta flow in 20 healthy volunteers and 14 patients 2 years following mitral repair for degenerative mitral regurgitation. Additional subgroup analysis was performed between

mitral annuloplasty bands and the Physio II annuloplasty ring (Edwards Lifesciences, Irvine, Calif). While impossible to make any definitive conclusions because of the small numbers and necessary computational assumptions, the authors predictably observed difference in flow patterns with mitral repair compared with healthy volunteers. While Morichi and colleagues⁹ attempted a comparison of vortex patterns between bands and rings, the results cannot be relied on due to the very small sample size and nonstandardized reconstructive strategy. The present study, however, reminds us that mitral valve disease and repair and replacement techniques, by definition, distort the physiological vortices seen in a healthy heart (Figure 1). This effect is most exaggerated in patients with dual orifice valves after percutaneous or surgical edge-to-edge repair and mechanical mitral valve replacement.¹⁰ By and large, surgeons have developed means to cure mitral regurgitation in most patients who undergo mitral valve repair. Should the next frontier in mitral valve reconstruction then be preservation of physiological blood flow patterns through the post-repair LV? To answer this question will require functional and clinical correlates.

We need to know whether the altered LV vorticity and observed aortic outflow patterns described by the authors relate to reduced functional capacity or worse clinical outcomes. It is unclear whether this is the case, as multiple studies suggest preserved life expectancy and functional status when mitral repair is undertaken early in the course of degenerative mitral valve disease.

In the arena of available structural heart disease therapies, flow dynamics will likely become a central player and may help improve equipoise when deciding on optimal treatment strategies. We applaud the authors for reminding us that as we repair mitral valves, we should not limit our focus to preventing retrograde flow into the atrium but should also consider how the blood will flow through the left ventricle and beyond. Larger-scale studies should be thus encouraged if we hope to achieve a useful translation into clinical practice.

References

1. Wells FC, Crowe T. Leonardo da Vinci as a paradigm for modern clinical research. *J Thorac Cardiovasc Surg.* 2004;127:929-44.
2. Bellhouse BJ, Bellhouse FH. Mechanism of closure of the aortic valve. *Nature.* 1968;217:86-7.
3. Bellhouse BJ. Fluid mechanics of a model mitral valve and left ventricle. *Cardiovasc Res.* 1972;6:199-210.
4. Hong GR, Pedrizzetti G, Tonti G, Peng Li, Wei Z, Kim JK, et al. Characterization and quantification of vortex flow in the human left ventricle by contrast echocardiography using vector particle image velocimetry. *JACC Cardiovasc Imaging.* 2008;1:705-17.
5. Kim WY, Walker PG, Pedersen EM, Poulsen JK, Oyre S, Houliand K, et al. Left ventricular blood flow patterns in normal subjects: a quantitative analysis by three-dimensional magnetic resonance velocity mapping. *J Am Coll Cardiol.* 1995;26:224-38.
6. Pedrizzetti G, la Canna G, Alfieri O, Tonti G. The vortex—an early predictor of cardiovascular outcome? *Nat Rev Cardiol.* 2014;11:545-53.
7. Kilner PJ, Yang GZ, Wilkett AJ, Mohladdlin RH, Firmin DN, Yacoub MH. Asymmetric redirection of flow through the heart. *Nature.* 2000;404:759-61.
8. Collià D, Vukicevic M, Meschini V, Zovatto L, Pedrizzetti G. Simplified mitral valve modeling for prospective clinical application of left ventricular fluid dynamics. *J Comput Phys.* 2019;398:108895.
9. Morichi H, Itatani K, Yamazaki S, Numata S, Nakaji K, Tamaki N, et al. Influences of mitral annuloplasty on left ventricular flow dynamics assessed with 3-dimensional cine phase-contrast flow magnetic resonance imaging. *J Thorac Cardiovasc Surg.* 2022;163:947-59.
10. Mele D, Smarrazzo V, Pedrizzetti G, Capasso F, Pepe M, Severino S, et al. Intracardiac flow analysis: techniques and potential clinical applications. *J Am Soc Echocardiogr.* 2019;32:319-32.

See Article page 947.

Commentary: In vortices veritas—quantitative approach

Michal Schäfer, PhD,^a Matthew L. Stone, MD, PhD,^b James Jagers, MD,^b Lorna P. Browne, MD,^c and Max B. Mitchell, MD^b

Vortices generated along the valvular surfaces are governed by hemodynamic forces, anatomic boundary conditions, and myocardial biomechanics. Hence, studying their qualitative and quantitative nature requires comprehensive

Left ventricular velocity and vorticity.

CENTRAL MESSAGE

Qualitative and quantitative 4D-flow MRI analysis enables comprehensive investigation of the intracardiac flow hemodynamic state.

From the ^aDivision of Cardiology, Heart Institute, ^bSection of Congenital Heart Surgery, Heart Institute, and ^cDepartment of Radiology, Children's Hospital Colorado, University of Colorado Denver | Anschutz Medical Campus, Aurora, Colo.

Disclosures: The authors reported no conflicts of interest.

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

Received for publication May 24, 2020; revisions received May 24, 2020; accepted for publication May 25, 2020; available ahead of print June 27, 2020.

Address for reprints: Michal Schäfer, PhD, Department of Cardiology, Children's Hospital Colorado, 13123 E 16th Ave, Aurora, CO 80045-2560 (E-mail: michal.schafer@cuanschutz.edu).

J Thorac Cardiovasc Surg 2022;163:964-6
0022-5223/\$36.00

Copyright © 2020 by The American Association for Thoracic Surgery
<http://dx.doi.org/10.1016/j.jtcvs.2020.05.112>

dimensional evaluation by 4-dimensional-flow magnetic resonance imaging (4D-flow MRI). The rising number of studies using 4D-flow MRI and improved accessibility to complex postprocessing platforms shifts this imaging