Editorial

4D flow imaging—state of the art

Michael Markl[1,2], **Michael D. Hope**[3,4]

[1]Department of Radiology, Northwestern University, Feinberg School of Medicine, Chicago, IL, USA; [2]Department of Biomedical Engineering, Northwestern University, McCormick School of Engineering, Evanston, IL, USA; [3]Department of Radiology and Biomedical Imaging, University of California, San Francisco, CA, USA; [4]Radiology Service, San Francisco Veterans Affairs Health Care System, San Francisco, CA, USA

Correspondence to: Michael D. Hope, MD. San Francisco Veterans Affairs Health Care System, 4150 Clement St, Box 114, San Francisco, CA 94121, USA. Email: michael.hope@ucsf.edu.

Submitted Dec 02, 2021. Accepted for publication Mar 22, 2022.
doi: 10.21037/acs-2021-bav-15
View this article at: https://dx.doi.org/10.21037/acs-2021-bav-15

4D flow magnetic resonance imaging (MRI) has emerged as a versatile imaging technique for the in-vivo measurement of cardiovascular 3D hemodynamics (1). The development of 4D flow MRI has greatly benefited the understanding bicuspid aortic valve (BAV) over the last two decades and has supported a flow-mediated mechanism for why patients with BAV frequently develop aortopathy such as aortic dilation, aneurysm or dissection (2).

Initial studies suggested a possible clinical application for 4D flow in the evaluation of BAV with unique flow patterns beautifully revealed by dynamic 3D visualizations. Laminar systolic flow was exhibited for healthy volunteers, whereas a range of distorted flow patterns were seen in patients with aortic valve disease such as BAV and/or dilated aortas. As more patients with BAV were studied, it became evident that many had characteristic helical systolic flow through the ascending aorta, and that this helical flow was seen even in the absence of aortic valve stenosis or aortic dilation. Several larger studies characterized the range of abnormal flow patterns seen and suggested the diagnostic potential of 4D flow in patients with BAV (3-5). The basic premise was that the abnormal flow patterns found with BAV promoted aortic dilation by placing undue hemodynamic stress on the ascending aortic wall. By characterizing this abnormal flow with 4D flow MRI, patients with BAV at increased risk for aortic disease progression could be identified.

The next phase of the evolution of 4D flow for the evaluation of BAV was a shift from qualitative imaging of flow patterns toward a focus on quantitative parameters to better reflect the range of abnormal hemodynamic stresses at play in the ascending aorta. 4D flow derived parameters including flow angle, flow displacement and wall shear stress (WSS) were developed to elucidate this relationship between altered systolic 3D flow dynamics and the aorta wall. Elevated WSS has shown particular promise as it is associated with vessel remodeling, weakening and endothelial cell injury, and can be estimated from the near wall velocity gradient that 4D flow imaging captures. A recent study of patients with BAV undergoing ascending aortic resection has shown that extracellular matrix (ECM) dysregulation and elastic fiber degeneration on histopathology correlated with regions of elevated aortic WSS estimated from preoperative 4D flow imaging (6).

Broader application of 4D flow MRI has been hindered by long scan times and cumbersome data processing and analysis, limiting reproducibility and clinical translation. In tandem with the development of reliable quantitative imaging parameters in the last decade, there has been a push to make 4D flow MRI faster and easier to use in the clinical setting. Novel acceleration techniques such as compressed sensing have reduced scan times to under five minutes—a radical improvement from imaging sessions that once regularly took over thirty minutes (7). Interpretation of 4D flow MRI no longer requires a dedicated research team. Post-processing workflows have been streamlined and visualization and analysis of data have become more straightforward. A number of commercial vendors now offer dedicated software packages for 4D flow analysis that can automate segmentation of the aorta and present key hemodynamic data in standardized formats.

BAV aortopathy has proved to be a challenging topic to study with 4D flow MRI. Aortic growth is slow (less than 1–2 mm/year for most cases of BAV), meaning that lengthy follow-up is needed to demonstrate the prognostic

value of 4D flow parameters to identify patients at risk for developing aortopathy. Many of the cohorts reported on are small, owing to earlier technical challenges that limited studies to single academic centers, and heterogenous in terms of crucial clinical factors such a valve leaflet fusion pattern, degree of concomitant stenosis and regurgitation, and patient age. To compound these problems, thresholds for elective aortic repair with BAV have fluctuated considerably in the last two decades, with thresholds as low as 4 cm proposed in 2010 by the American Heart Association. This has led to overtreatment of the disease and a paucity of patients presenting for imaging with progressive aortic disease.

Despite these challenges, there continues to be encouraging data. A recent larger study has bolstered the understanding that BAV phenotypes (i.e., right-left versus right-noncoronary) result in differently oriented systolic jets in the ascending aorta which, in turn, are associated with unique aortic dilation morphologies (8). Preliminary studies have suggested a correlation between abnormal flow with BAV and increased rates of aortic dilation (9). Newly published data based on over 5-years of follow-up shows that elevated WSS derived from 4D flow is associated with faster aortic growth, and thus may help determine which patients would benefit from closer surveillance (10). As 4D flow MRI becomes more broadly and regularly used with faster imaging and automated workflows for calculation of standardized parameters, we anticipate that larger datasets will become available and the prognostic role of 4D flow MRI for progressive aortopathy with BAV will be more convincingly demonstrated.

Acknowledgments

Funding: This work was supported by National Institutes of Health, Grant No. R01HL115828.

Footnote

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Dyverfeldt P, Bissell M, Barker AJ, et al. 4D flow cardiovascular magnetic resonance consensus statement. J Cardiovasc Magn Reson 2015;17:72.
2. Verma S, Siu SC. Aortic dilatation in patients with bicuspid aortic valve. N Engl J Med 2014;370:1920-9.
3. Hope MD, Hope TA, Meadows AK, et al. Bicuspid aortic valve: four-dimensional MR evaluation of ascending aortic systolic flow patterns. Radiology 2010;255:53-61.
4. Bissell MM, Hess AT, Biasiolli L, et al. Aortic dilation in bicuspid aortic valve disease: flow pattern is a major contributor and differs with valve fusion type. Circ Cardiovasc Imaging 2013;6:499-507.
5. Mahadevia R, Barker AJ, Schnell S, et al. Bicuspid aortic cusp fusion morphology alters aortic three-dimensional outflow patterns, wall shear stress, and expression of aortopathy. Circulation 2014;129:673-82.
6. Guzzardi DG, Barker AJ, van Ooij P, et al. Valve-Related Hemodynamics Mediate Human Bicuspid Aortopathy: Insights From Wall Shear Stress Mapping. J Am Coll Cardiol 2015;66:892-900.
7. Neuhaus E, Weiss K, Bastkowski R, et al. Accelerated aortic 4D flow cardiovascular magnetic resonance using compressed sensing: applicability, validation and clinical integration. J Cardiovasc Magn Reson 2019;21:65.
8. Rodríguez-Palomares JF, Dux-Santoy L, Guala A, et al. Aortic flow patterns and wall shear stress maps by 4D-flow cardiovascular magnetic resonance in the assessment of aortic dilatation in bicuspid aortic valve disease. J Cardiovasc Magn Reson 2018;20:28.
9. Hope MD, Wrenn J, Sigovan M, et al. Imaging biomarkers of aortic disease: increased growth rates with eccentric systolic flow. J Am Coll Cardiol 2012;60:356-7.
10. Soulat G, Scott MB, Allen BD, et al. Association of Regional Wall Shear Stress and Progressive Ascending Aorta Dilation in Bicuspid Aortic Valve. JACC Cardiovasc Imaging 2022;15:33-42.

Cite this article as: Markl M, Hope MD. 4D flow imaging—state of the art. Ann Cardiothorac Surg 2022;11(4):468-469. doi: 10.21037/acs-2021-bav-15