We present findings in a 79-year-old man after transcatheter aortic valve implantation (TAVI) for severe symptomatic aortic stenosis using a 26-mm Edwards Lifesciences Sapien 9000TFX valve. His predicted risk of operative mortality (Society of Thoracic Surgery score) was 12% on the basis of the following comorbidities: 2 previous coronary artery bypass operations, New York Heart Association functional class IV, hypertension, mild lung disease, ejection fraction of 25%, creatinine of 1.2 mg/dL, atrial fibrillation, and peripheral vascular disease. He underwent transapical delivery of the valve on January 5, 2011, without complication. His initial postoperative echocardiogram showed moderate aortic regurgitation (AR), mean gradient of 49 mm Hg, and ejection fraction of 25%. After discharge, the patient was reevaluated for recurrent dyspnea.

To gain further insight into the systemic implications of AR on hemodynamics of the left ventricular outflow tract in relation to potential congestive heart failure after TAVI, we performed time-resolved 3-dimensional (3D) magnetic resonance velocity mapping (4-dimensional [4D] flow magnetic resonance imaging [MRI]) 6 months postoperatively. The study was approved by the institutional review board, and informed consent was obtained from the patient. Magnetic resonance imaging examination (1.5T Espree, Siemens, Germany) included 4D flow (velocity sensitivity $=150$ cm/s, spatial/temporal resolution $=2.5 \times 2.1 \times 3.2$ mm$^3$/42 ms) and dynamic 2D cine imaging of the heart (steady-state free precession, spatial/temporal resolution $=1.4 \times 1.6 \times 8$ mm$^3$/49 ms).

Echocardiographic assessment of aortic insufficiency was performed using standard parasternal and apical views with Nyquist limit $>50$ cm/s. Echocardiography demonstrated 2 jets of aortic regurgitation and was graded mild to moderate. Regurgitant volume and fraction were 28 mL and 41%, respectively (Figure 1).

Four-dimensional flow MRI was used for 3D flow visualization (EnSight, CEI, North Carolina) based on 3D streamlines depicting the direction of blood flow as traces along the measured blood flow velocities (Figure 2). Time-resolved 3D pathlines were employed to illustrate the temporal evolution of blood flow in the left ventricular outflow tract and thoracic aorta (online-only Data Supplement Movie). Vector graphs were used to visualize flow profiles and retrograde flow jets below the aortic valve (Figure 3). Two-dimensional cine images of the left ventricular outflow tract were fused with the 4D flow data to coregister 3D hemodynamics and left ventricular outflow tract anatomy. In addition, the 4D flow data were used to retrospectively quantify retrograde flow and retrograde fraction as well as peak systolic and diastolic retrograde velocities above and below the valve.

Three-dimensional streamline visualization (Figure 2) revealed intricate flow alterations that are absent in normal aortic flow. Strongly asymmetrical systolic left ventricular outflow with a flow jet forming along the right anterior outer curvature of the ascending aorta (Figure 1, left, open arrows) caused the development of marked helical flow (Figure 2, online-only Data Supplement Movie).
yellow arrows). Helix flow was fully developed during mid-systole (yellow arrows, t\(=170\) ms and 205 ms) and extended toward the aortic arch during early and mid-diastole (t\(=396\) ms and 525 ms). The complex multidirectional and phasically changing aortic flow can be best appreciated if viewed dynamically as shown in the online-only Data Supplement Movie.

Vector graph visualization of flow in an analysis plane below the valve (Figure 3) revealed a complex retrograde flow jet pattern. Two clearly identifiable jets dynamically changed their location and direction during early and mid-diastole. Peak systolic velocity was high in the ascending aorta (2.1 m/s). Substantial diastolic retrograde peak velocities (0.7 m/s) were detected both above and below the valve. Analysis further revealed a moderate retrograde regurgitant fraction of 20% and retrograde flow of 19 mL (antegrade flow 92 mL). Because of the presence of metal artifacts (signal dropout) at the location of the inserted valve, visualization or quantification of flow was not possible inside the valve, which may explain why the residual AR as measured by 4D MRI was less severe compared with echocardiography. Nevertheless, the visualization of a dual jet pattern below the valve associated with perivalvular leak was possible with 4D flow MRI. The case also demonstrated unexpectedly complex abnormal flow after TAVI. A novel finding using 4D flow MRI was the substantial flow derangement in the aorta (marked helix flow). These findings clearly differed from normal flow patterns such as a mild-to-moderate right-handed systolic outflow helix and mild early diastolic retrograde flow in the ascending aorta and arch.\(^3\) Our findings suggest that the hemodynamic flow pattern after TAVI may be more complex than previously anticipated. Aortic helix flow may indicate regions with abnormal wall shear stress, which can change endothelial function and create areas at risk for vascular remodeling and aortic dilatation.

These findings are of particular interest in light of a recent study in high-risk patients with severe aortic stenosis, which showed that transcatheter and surgical procedures for aortic-valve replacement were associated with similar rates of survival but there were important differences in perioperative risks. Transcatheter replacement resulted in much more frequent perivalvular AR possibly related to less seamless alignment of the transcatheter prosthesis compared with surgically repaired valves. However, no reliable and validated method exists to quantify multiple jets of perivalvular AR by echocardiography.\(^4\) The presented case illustrates the potential of 4D flow MRI to complement echocardiography in the assessment of aortic regurgitation in such patients and adds additional information on complex aortic hemodynamics and retrograde jet patterns.

Optimal predictors and their correlation with long-term outcome after TAVI are still missing and require further investigations in longitudinal studies using larger cohorts of patients. Furthermore, studies are warranted to compare...
hemodynamics after TAVI to normal and age-matched controls and aortic valve replacement. Our findings indicate the potential role of methods such as 4D flow MRI for follow-up in these patients.

Disclosures
Dr Malaisri is an investigator in the Edward Lifesciences Placement of AoRTic TraNscathetER Valve (PARTNER) I and II trials.

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