We present findings in a 68-year-old man listed for heart transplantation (T status, which is similar to US status 1B) who suffered from long-term heart failure due to dilative cardiomyopathy. After recurrent cardiac decompensation, he was supported with a left ventricular assist device (Synergy, CircuLite, Saddle Brook, NJ). After 17 weeks of support, the pump had to be deactivated because of recurrent system failure and thromboembolic events. As a consequence, he was registered as a high-urgency patient and had to wait for another 16 weeks before an organ became available.

Orthotopic heart transplantation using the bicaval technique combined with explantation of the left ventricular assist device was uneventful. Intraoperatively, 3 additional procedures had to be performed: (1) A patch repair of the upper right pulmonary vein was performed after explantation of the left atrial cannula of the left ventricular assist device; (2) a significant discrepancy in the diameters of the native and the transplanted ascending aorta (34 versus 24 mm) made a tapered diameter reduction in the aortic anastomosis necessary; and (3) the donor pulmonary trunk was directly connected to the branching point of the left and right pulmonary arteries. Immediately after heart transplantation and while still in the operating room, the patient was examined by transesophageal echocardiography and pulmonary artery catheterization (Swan-Ganz catheter, Edwards Lifesciences Corp, Irvine, CA). The catheter measurement revealed an elevated systolic pressure gradient in the pulmonary artery of 10 mm Hg, indicative of a pulmonary stenosis; however, this was not supported by transesophageal echocardiography or other hemodynamic data (central venous pressure, pressure in the right ventricle, and cardiac output). After a smooth intraoperative course, the patient made an uncomplicated recovery and was discharged from the hospital within 30 days after heart transplantation. All predischarge examinations, including transesophageal echocardiography, chest radiographs, laboratory data, and ECG, were within normal limits.

Because of the controversial findings between transesophageal echocardiography and invasive pressure gradient measurements, whole-heart flow-sensitive 4-dimensional magnetic resonance imaging was performed on postoperative day 38. The aim was to evaluate arterial and venous anatomy and to assess time-resolved 3-dimensional (3D) blood flow in the whole heart and surrounding large venous and arterial vessels. Data acquisition was performed on a routine 3T magnetic resonance system (Magnetom TRIO, Siemens, Erlangen, Germany; flip angle 7°, velocity sensitivity 150 cm/s, spatial resolution 3.0×2.5×3.2 mm³, echo time 2.4 ms, repetition time 4.8 ms, temporal resolution 38.0 ms, prospective ECG gating, respiratory navigator gating, and total scan time of 20 minutes).

Flow-sensitive 4-dimensional magnetic resonance imaging was used to derive information on the venous and arterial vascular geometry by calculation of 3D phase-contrast magnetic resonance angiography. Next, 3D phase-contrast magnetic resonance angiography was combined with 3D flow visualization, which was based on the calculation of 3D streamlines depicting the direction of blood flow as traces along the measured blood flow velocities at a given time within the cardiac cycle (EnSight, CEI Inc., Apex, NC). Streamlines originated from emitter planes in the ascending aorta, the inferior and superior vena caval veins, the pulmonary trunk, left and right pulmonary arteries, and pulmonary veins. In addition, time-resolved 3D pathlines were used to depict the temporal evolution of blood flow through the different cardiac and vascular compartments.

Blood flow and peak systolic velocities were quantified retrospectively in the pulmonary trunk, the left and right pulmonary arteries, and the ascending aorta. Findings in the patient were compared with results in 4 young healthy volunteers (all men, 25 to 27 years of age) examined with the same magnetic resonance technique.

Three-dimensional phase-contrast magnetic resonance angiography (Figure 1) showed the anatomy of the heart and
surrounding vessels after transplantation. The marked diameter change at the site of the aortic anastomosis (solid black arrow) and the transition from the donor pulmonary trunk to the left and right pulmonary branches (open black arrows) are clearly visible in Figure 1.

Three-dimensional streamline visualization in the whole heart and surrounding vessels is illustrated in Figure 2, and showed normal venous filling during diastole (left column) with undisturbed flow from the caval and pulmonary veins into the right and left atrium and ventricle. In contrast, visualization of systolic arterial outflow (Figure 2, right column) revealed a number of distinct flow alterations that were absent in healthy control subjects. Strong vortical and helical flow was observed at several locations throughout the aorta (Figure 2, lower right). For both aorta and pulmonary artery, flow disturbances were most pronounced directly distal to the anastomosis, as shown in the magnification in Figure 3. Regionally abnormal flow manifested as vortices in the left and right pulmonary arteries (Figure 3A) and helix patterns and sudden flow deceleration in the aorta (Figure 3B). The complex multidirectional and phasically changing flow through the heart can be best appreciated if viewed dynamically, as shown in Movie I in the online-only Data Supplement.

As evident from Figures 1 through 3, pulmonary stenosis could be ruled out in agreement with earlier findings by transesophageal echocardiography. However, despite the absence of pulmonary stenosis or regurgitation, substantially enhanced systolic peak velocities in the entire pulmonary trunk and even in the left and right pulmonary arteries (Figure 2, top right, white arrows) were observed. Peak systolic velocities were moderately increased in the aorta (by 32%; 1.75 m/s in the patient versus 1.33±0.13 m/s in healthy volunteers) and substantially higher (by 83%) in the pulmonary trunk (1.69 m/s in the patient versus 0.92±0.03 m/s in healthy volunteers). Analysis additionally revealed a normal right-to-left pulmonary artery flow ratio (1.1 for the patient versus 1.1±0.1 for healthy volunteers) and pulsatility index in the aorta (4.6 versus 4.4±0.6, respectively) and in the pulmonary trunk (3.0 versus 3.9±0.7, respectively). Aortic or pulmonary regurgitation in the patient was negligible (regurgitant fraction 5% in the aorta and 2% in the pulmonary trunk).

The cause of elevated velocities in the pulmonary arteries and what consequences should be expected from this finding are not fully understood. Nevertheless, increased velocities may offer an explanation of the elevated pulmonary pressure gradient found by intraoperative catheter measurements, which was falsely associated with pulmonary stenosis.

Our findings suggest that the hemodynamic situation after heart transplantation may be more complex than previously
believed. Despite excellent clinical outcome in this patient, abnormal flow clearly exists. The possibility of detecting flow patterns such as vortex flow or identifying regions with increased velocities may help to identify regions with abnormal flow and altered shear forces acting on the vessel wall. It is known from the literature that unfavorable shear forces at the vessel wall can change endothelial function and create areas at risk for vascular remodeling. The identification of such flow patterns may thus help to identify previously nonassessable early markers for the development of secondary pathologies, as, for example, in the beginning of transplant rejection or cardiac allograft vasculopathy. However, optimal predictors and their correlation with long-term outcome are still missing and subject to further investigations in longitudinal studies with larger cohorts of patients.

In summary, we report the first comprehensive evaluation of the hemodynamic response of the entire cardiovascular system after heart transplantation. Our findings indicate that even successful heart transplantation can induce distinct regional flow alterations that may be missed by standard techniques, which illustrates the potential role and importance of methods such as flow-sensitive 4-dimensional magnetic resonance imaging for follow-up in these patients.

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Disclosures
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Comprehensive 4-Dimensional Magnetic Resonance Flow Analysis After Successful Heart Transplantation Resolves Controversial Intraoperative Findings and Reveals Complex Hemodynamic Alterations

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