In Vivo 3-Dimensional Flow Connectivity Mapping After Extracardiac Total Cavopulmonary Connection

Alex Frydrychowicz, MD; Raoul Arnold, MD; Andreas Harloff, MD; Christian Schlensak, MD; Jürgen Hennig, PhD; Mathias Langer, MD, MBA; Michael Markl, PhD

We present findings in an 18-year-old female patient with a double-inlet single ventricle 12 years after extracardic total cavopulmonary connection (TCPC)[1] who also presented with a Waldhausen repair of aortic coarctation. To evaluate arterial and venous anatomy and to assess time-resolved 3-dimensional (3D) blood flow in the venous and pulmonary system, flow-sensitive 4-dimensional magnetic resonance (MR) imaging was performed on a routine 3T MR system (Magnetom TRIO, Siemens, Germany; flip angle=15°, velocity sensitivity=150 cm/s, spatial resolution $2.4\times1.8\times2.8$ mm^3, echo time (TE)=2.5 ms, repetition time (TR)=5.0 ms, temporal resolution=40.0 ms, prospective ECG gating, respiratory navigator gating).[2] Flow-sensitive 4D MR imaging cannot only be used for the analysis of blood flow but also to derive additional information on vascular geometry by the calculation of a 3D phase contrast (PC) MR angiography. In contrast to conventional contrast-enhanced arterial MR angiography, 3D PC-MR angiography was used to depict venous and arterial structures within the same data volume and acquisition (see Figure 1). Moreover, the resulting images can be combined with 3D blood flow visualization to analyze the spatially coregistered vascular hemodynamics and anatomy (see Figure 2).

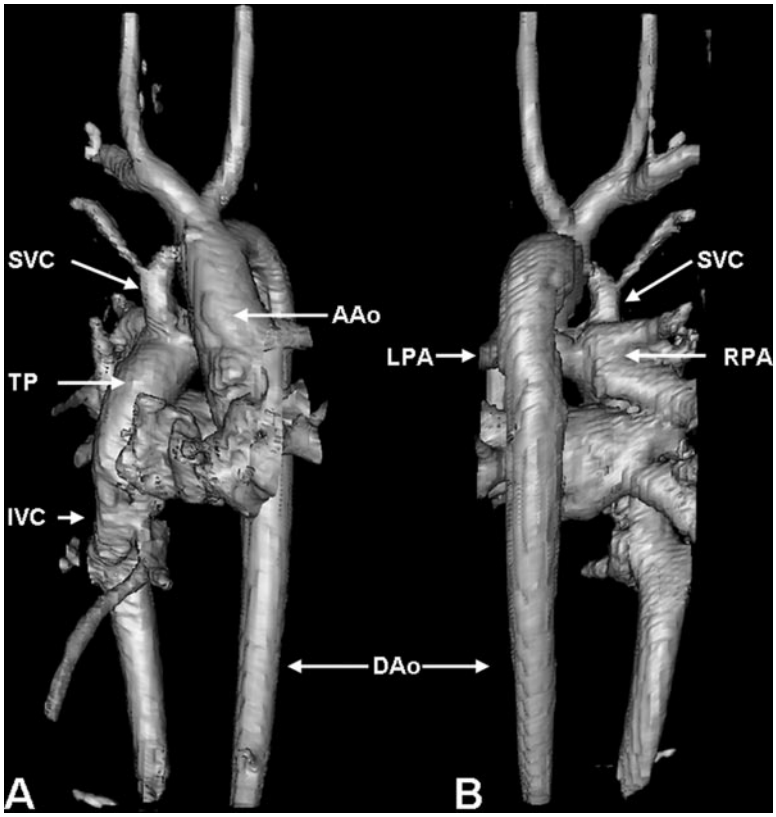

Figure 1. Volume-rendered images from 3D phase-contrast MR angiography at 3T elucidate the altered anatomy after total cavopulmonary connection. A, Anterior view. B, Posterior view. SVC indicates superior vena cava; TP, pulmonary trunk; AAo, ascending aorta; and DAo, descending aorta.

From the Department of Diagnostic Radiology and Medical Physics (A.F., J.H., M.L., M.M.), Department of Pediatric Cardiology (R.A.), Department of Neurology and Clinical Neurophysiology (A.H.), and Department of Cardiovascular Surgery (C.S.), University Hospital Freiburg, Freiburg, Germany.

The online-only Data Supplement, which consists of Movies I and II, can be found at http://circ.ahajournals.org/cgi/content/full/118/2/e16/DC1.

Correspondence to Dr med Alex Frydrychowicz, MD, University Hospital Freiburg, Department of Diagnostic Radiology and Medical Physics, Hugstetter Str 55, 79106 Freiburg, Germany. E-mail alex.frydrychowicz@uniklinik-freiburg.de

(*Circulation.* **2008;118:e16-e17.**)

Circulation **is available at http://circ.ahajournals.org** **DOI: 10.1161/CIRCULATIONAHA.107.761304**

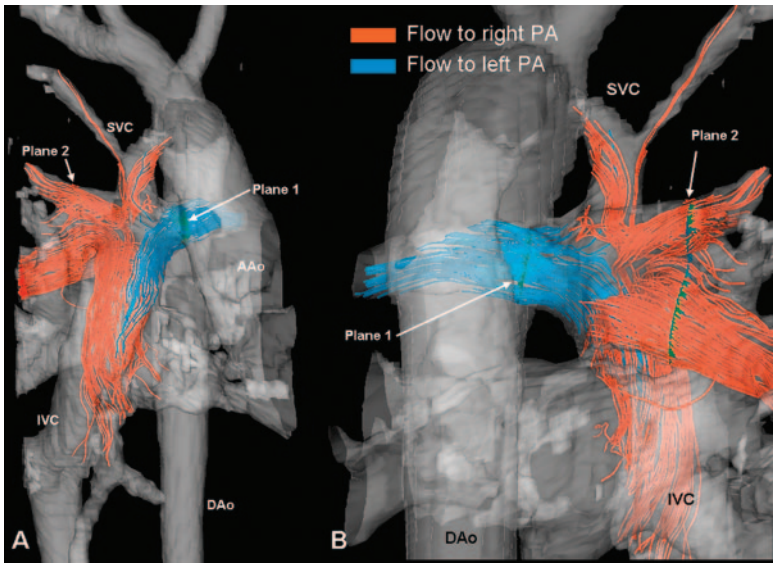

Figure 2. Three-dimensional flow connectivity mapping of blood flow contributing to the filling of the RPA and LPA on the basis of forward/backward tracking of the measured 3D blood flow velocities. A, Anterior view. B, Posterior view. After placement of 2 planes in the proximal LPA and RPA, red color shows the flow into the RPA and blue-colored stream lines reveal blood flow to the LPA from the IVC. Abbreviations as in Figure 1.

Three-dimensional flow connectivity mapping was based on the calculation of 3D streamlines depicting the direction of blood flow as traces along the measured velocity vector field at a given time within the cardiac cycle (EnSight software, CEI, Apex, NC). Instead of following the path of the blood flow along the direction of the flow as described before,[3,4] 3D flow connectivity mapping uses both backward and forward tracing of blood flow. By placing emitter planes in the left and right pulmonary arteries (LPA and RPA), we were able to identify the vascular origin of LPA and RPA filling.

We present images from 3D PC-MR angiography (Figure 1), which shows the altered anatomy of the central thoracic vessels and the direct connection of the inferior vena cava (IVC) and superior vena cava to the pulmonary artery. Three-dimensional flow connectivity mapping is illustrated in Figure 2 for the anterior (A) and posterior (B) view of the TCPC. Emitter planes used to initiate streamline calculation were placed in the proximal right and left pulmonary artery. Color coding of the resulting streamlines was used to visualize flow pathways from the venous system into the RPA (red) and LPA (blue). The resulting images, which can be viewed as movies in the online-only Data Supplement (Movies I and II), show a filling of the RPA by both the IVC and superior vena cava, whereas the LPA is predominantly filled by the IVC.

These findings are inconsistent with earlier reports and suggest that blood flow in single-ventricle patients after TCPC might be more complex than previously thought.[5,6] Numerous reports on model simulations[7] and in vivo follow-up examinations after TCPC have been presented before. However, optimal predictors are still missing for the long-term outcome and an optimization of the procedure to reduce secondary complications such as ventricular dysfunction, thromboembolism, arrhythmias, or protein-losing enteropathy.[5,6,8]

New diagnostic tools such as flow-sensitive 4D MR imaging[2,9] and 3D flow connectivity mapping might help in identifying the extent of superior and inferior caval vein contribution to pulmonary blood flow. They potentially permit a more precise monitoring of vascular hemodynamics in order to identify and prevent secondary complications in the follow up after TCPC.

Sources of Funding

Dr. Markl receives governmental funding from Deutsche Forschungsgemeinschaft Grant MA 2383/4-1 and the Bundesministerium für Bildung und Forschung, grant 01EV0706.

Disclosures

None.

References

1. Fontan F, Baudet E. Surgical repair of tricuspid atresia. *Thorax*. 1971; 26:240–248.
2. Markl M, Harloff A, Zaitsev M, Jung B, Weigang E, Langer M, Hennig J, Frydrychowicz A. Time resolved 3D MR velocity mapping at 3T: improved navigator gated assessment of vascular anatomy and blood flow. *J Magn Reson Imaging*. 2007;25:824–831.
3. Buonocore MH. Visualizing blood flow patterns using streamlines, arrows, and particle paths. *Magn Reson Med*. 1998;40:210–226.
4. Frydrychowicz A, Harloff A, Jung B, Zaitsev M, Weigang E, Bley TA, Langer M, Hennig J, Markl M. Time-resolved, 3-dimensional magnetic resonance flow analysis at 3 T: visualization of normal and pathological aortic vascular hemodynamics. *J Comput Assist Tomogr*. 2007;31:9–15.
5. Fogel MA, Weinberg PM, Rychik J, Hubbard A, Jacobs M, Spray TL, Haselgrove J. Caval contribution to flow in the branch pulmonary arteries of Fontan patients with a novel application of magnetic resonance presaturation pulse. *Circulation*. 1999;99:1215–1221.
6. Gutberlet M, Venz S, Kahl A, Ehrenstein T, Puls R, Hosten N, Frei U, Felix R. Blood flow quantification in hemodialysis shunts by phase contrast magnetic resonance angiography (PC-MRA) compared with duplex sonography [in German]. *Rofo*. 1998;169:163–169.
7. de Zelicourt DA, Pekkan K, Wills L, Kanter K, Forbess J, Sharma S, Fogel M, Yoganathan AP. In vitro flow analysis of a patient-specific intraatrial total cavopulmonary connection. *Ann Thorac Surg*. 2005;79: 2094–2102.
8. Fogel MA, Weinberg PM, Hoydu A, Hubbard A, Rychik J, Jacobs M, Fellows KE, Haselgrove J. The nature of flow in the systemic venous pathway measured by magnetic resonance blood tagging in patients having the Fontan operation. *J Thorac Cardiovasc Surg*. 1997;114: 1032–1041.
9. Wigstrom L, Sjoqvist L, Wranne B. Temporally resolved 3D phase-contrast imaging. *Magn Reson Med*. 1996;36:800–803.