

## INNOVATIVE CLINICAL IMAGE

# 4D Flow MR Imaging Reveals a Decrease of Left Atrial Blood Flow in a Patient with Cardioembolic Cerebral Infarction after Pulmonary Left Upper Lobectomy

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We present the case of a 76-year-old woman who underwent left upper lobectomy for lung adenocarcinoma. Three days after the surgery, a thrombus was observed in the pulmonary vein (PV) stump. Four months after the surgery, we performed 4D flow MRI, which revealed decreased blood flow, not only in the left superior PV stump, but also over a widespread region around the left atrium-left superior PV junction. 4D flow MRI can clarify the altered hemodynamics underlying thrombus formation.

**Keywords:** 4D flow MRI, left upper lobectomy, cerebral infarction, thrombus formation

## Introduction

Cardioembolic cerebral infarction is one of the severe complications encountered after pulmonary lobectomy.<sup>1–5</sup> It has been hypothesized as being caused by thrombus formation in the pulmonary vein (PV) stump.<sup>1–3,6–9</sup> Recently, several studies have reported that a thrombus is detected in the PV stump in 3.3–3.6% of all patients, and only in patients undergoing left upper lobectomy (LUL) (13.5–17.9%). Ohtaka et al.<sup>10</sup> measured the blood flow velocity in the left superior (LS) PV stump by intraoperative ultrasonography, and clarified that there is a tendency toward decreased flow in the LSPV stump as compared to the other PV stumps. They also suggested that a slower flow in the LSPV stump may be predictive of thrombosis.

Recently, time-resolved 3D phase contrast (4D flow) MRI has been introduced clinically.<sup>11</sup> 4D flow MRI can acquire quantitative flow information in each voxel, allowing generation of both qualitative and quantitative flow images. In addition, the developing scan scheme [e.g. dual velocity encoding (VENC) scan] and acceleration technique (e.g.  $k-t$  acceleration technique) enable more precise capture of slow flow within the clinically acceptable scan time.<sup>12</sup> 4D flow MRI evaluation of left atrial (LA) hemodynamics has been reported.<sup>13–15</sup> Some of

these studies have attempted to clarify the cause of thrombus formation in patients with atrial fibrillation.<sup>14,15</sup> However, there is no report until date, in which 4D flow MRI was performed for the evaluation of LA thrombus formation after LUL. We examined the hemodynamics by 4D flow MRI in a patient who developed cerebral infarction as a complication after LUL.

## Case Reports

A 76-year-old woman underwent LUL for lung adenocarcinoma (cT1aN0M0 stage IA1) (Supplementary Fig. 1; Supplementary materials are available online). Three days after the surgery, she developed a stroke (Supplementary Fig. 2). Contrast-enhanced chest CT showed a thrombus in the LSPV stump (Fig. 1). Fortunately, with the early diagnosis, the patient was immediately started on treatment for stroke, and could be discharged on the 22nd day after the surgery. At 4 months after the surgery, contrast-enhanced MRA and subsequent dual-VENC 4D flow MRI were performed. For this IRP approved study (R1-08-1168), written informed consent was obtained from the patient prior to the imaging examinations. The 4D flow MRI parameters were as follows: 3T MRI unit (Achieva, Philips Healthcare, Best, The Netherlands), TR/TE 5.2/2.5 ms, flip angle 11°, dual-VENC acquisition, VENC 50–150 cm/s, 24 heart phase, axial-acquisition, field of view 280 × 280 × 140 mm, voxel size 1.75 × 1.75 × 2.00 mm<sup>3</sup>,  $k-t$  PCA acceleration factor 8, navigator-based respiratory triggering, and scan time of approximately 12 min. The blood flow velocity was quantified using the PGEM package of the PMOD software (Ver. 4.0, PMOD Technologies Ltd, Zurich, Switzerland). After co-registration of the contrast-enhanced MRA with the 4D flow MRI dataset using PMOD, we placed five VOIs in each of the following

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regions: the junction between the LA and each of the four PVs (LA–PV), and the LSPV stump. The average blood flow velocity during one cardiac cycle was measured in each VOI. The velocity in the patient was compared with that in eight volunteers [age 31.4 (26–36), six males]. The blood flow was visualized using GTFflow (Ver. 3.2. Gyrotools, Zurich, Switzerland).

Contrast-enhanced MRA did not reveal any thrombus at the time of the scanning. 4D flow MRI revealed a decrease in the rate of blood flow at the LA–LSPV junction and LSPV stump (Fig. 2). As shown in Table 1 and Fig. 3, the blood

flow velocity was the highest (15.1 cm/s) at the LA–right superior PV junction. However, the blood flow was also slower at the LA–LSPV junction and LSPV stump, as compared with that at the other LA–PV junctions (3.55 and 3.57 cm/s, respectively). Pathline analysis clearly showed that the blood flow from each of the other three PVs was directed to the mitral valve, whereas no flow was directed to the LA–PV junction (Fig. 4).

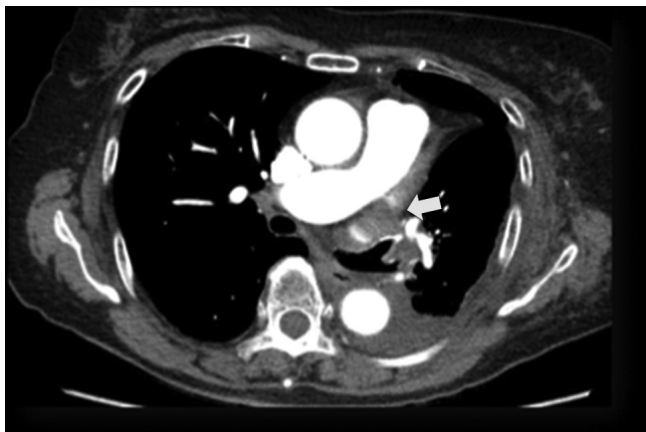
## Discussion

In the present case, 4D flow MRI allowed quantification of the decreased blood flow both at the LA–LSPV junction and the PV stump. In addition, pathline visualization clearly showed the hemodynamic cause of the decreased flow.

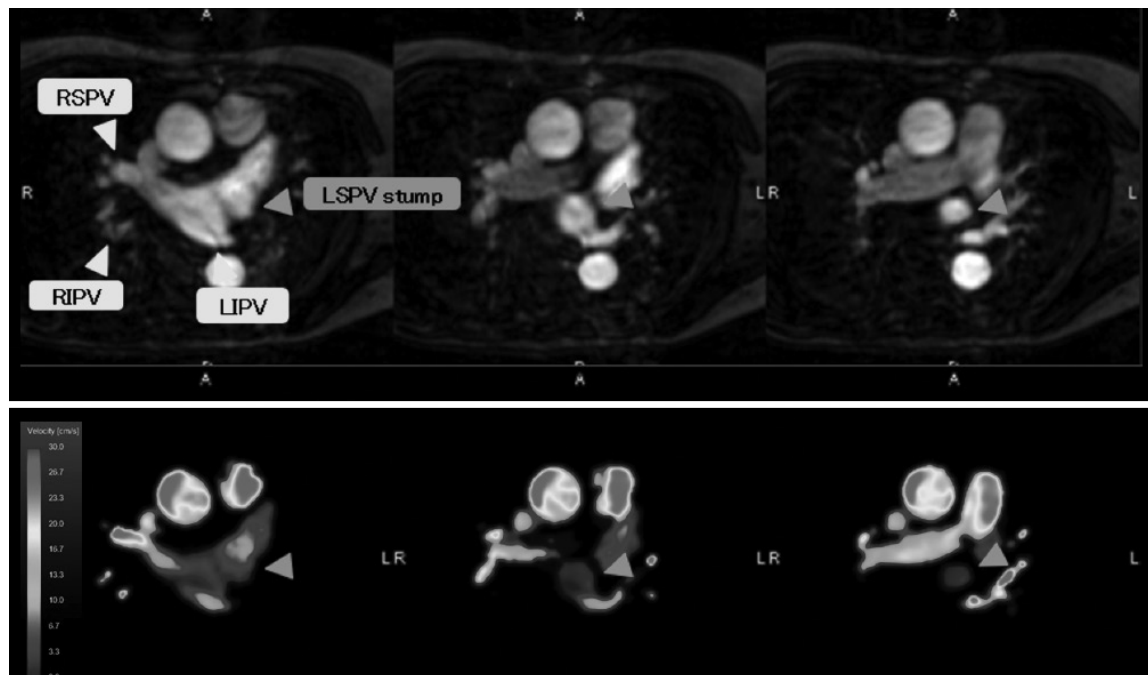
**Table 1** The averaged velocity of each region

Region	Velocity (cm/s)	
	Case	Volunteers
LA–RSPV junction	15.06	12.33 ± 2.86
LA–RIPV junction	6.74	12.90 ± 2.37
LA–LIPV junction	6.08	13.47 ± 3.03
LA–LSPV junction	3.55	13.34 ± 3.27
LSPV stump	3.57	–

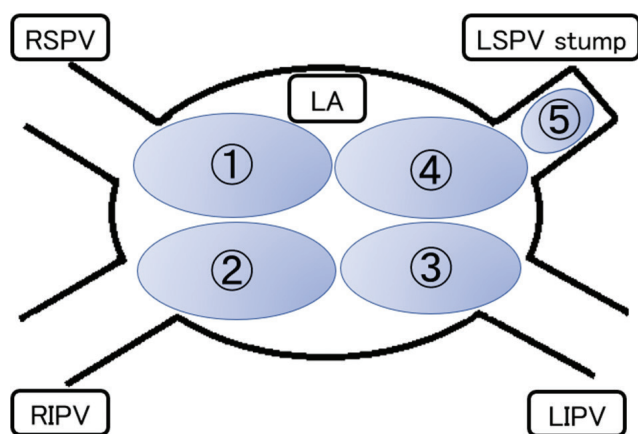
LA, left atrium; RSPV, right superior pulmonary vein; RIPV, right inferior pulmonary vein; LIPV, left inferior pulmonary vein; LSPV, left superior pulmonary vein.



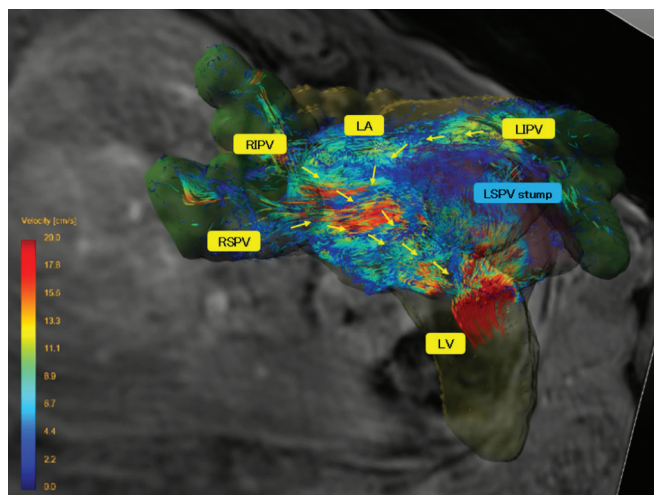
**Fig. 1** Contrast-enhanced chest CT on postoperative day 3. A thrombus is seen in the left superior pulmonary vein stump (arrow).



**Fig. 2** 2D images of contrast-enhanced MRA and 4D flow MRI. The upper row presents a contrast-enhanced MRA images and the lower row shows the velocity map derived from 4D flow MRI. Each pulmonary vein can be seen in the figure [right superior pulmonary vein (RSPV), right inferior pulmonary vein (RIPV), left inferior pulmonary vein (LIPV), left superior pulmonary vein (LSPV)]. Decreased flow is seen at LSPV stump and around the junction between the left atrium and the LSPV.



**Fig. 3** Blood flow velocity at five points; junction between the left atrium (LA) and right superior pulmonary vein (RSPV) (①), right inferior pulmonary vein (RIPV) (②), left inferior pulmonary vein (LIPV) (③) and left superior pulmonary vein (LSPV) (④), and the LSPV stump (⑤). Diagram shows the quantitative blood flow distribution at each of the five points. The blood flow velocity is the highest at the junction between the LA and RSPV, and slower at the LA–LSPV junction and LSPV stump than in other regions.



**Fig. 4** Pathline analysis of 4D flow MRI. Color-coded pathlines show the flow pattern in the left atrium. The green area represents blood from each of the right superior pulmonary vein (RIPV), right superior pulmonary vein (RSPV) and left inferior pulmonary vein (LIPV). The red area represents the left superior pulmonary vein (LSPV) stump. Pathlines are drawn from the VOI of each of three pulmonary veins (RSPV, RIPV and LIPV). The yellow arrows indicate the direction of the blood flow. All of the pathlines are directed to the mitral valve; there is no flow directed to the junction between the left atrium and the LSPV.

Previous studies suggested that the LSPV stump is longer than the stumps of the other PVs, which may be the reason for the stagnation of blood at the LSPV stump.<sup>2,3</sup> However, thrombosis can occur even in shorter LSPV stumps.<sup>16</sup> Additional mechanisms should be clarified. In the current study, 4D flow MRI showed a reduction of the blood flow rate not only in the LSPV stump, but also over a

widespread region around the LA–LSPV junction. Volumetric pathline visualization implied that the anatomical location and flow balance of the remaining PVs could lead to an altered flow distribution in the LA. Although further analysis should be performed in patients undergoing resection of other lobes or before LUL, 4D flow MRI allows elucidation of the altered hemodynamics underlying thrombus formation after surgery for lung cancer.

## Conflicts of Interest

The authors have no conflicts of interests to declare.

## Supplementary Information

Supplementary Figs. 1 and 2 are available online.

### Supplementary Fig. 1

Preoperative computed tomography (CT). An irregularly shaped nodular lesion is seen in the left upper lobe. The lesion was diagnosed as an adenocarcinoma by CT-guided needle lung biopsy.

### Supplementary Fig. 2

Brain diffusion-weighted images and apparent coefficient map on postoperative day 3. The images show cerebral infarction in the frontal lobe.

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