Initial experience characterizing a type I endoleak from velocity profiles using time-resolved three-dimensional phase-contrast MRI

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We report the first utilization of time-resolved three-dimensional phase contrast magnetic resonance imaging, termed 4D flow, to image a type I endoleak after endovascular aneurysm repair. The combination of 4D flow and a traditional magnetic resonance angiogram can aid in the accurate detection and characterization of endoleaks by combining the three-dimensional resolution of cross-sectional imaging with the temporally resolved velocity data of Doppler ultrasound. (J Vasc Surg 2009;49:1580-4.)

Endoleaks represent one of the most frequent radiologic findings after endovascular aneurysm repair (EVAR). Detection and accurate classification of the type of endoleak is integral in the selection of the appropriate intervention. Computed tomography angiography (CTA), duplex ultrasonography (US), and magnetic resonance angiography (MRA) have been used to follow patients, but there continue to be problems with determining the exact origin of the endoleak using these imaging modalities. We describe the first utilization of time-resolved three-dimensional phase contrast magnetic resonance imaging (4D flow) to aid in the identification and characterization of an endoleak.

Previous magnetic resonance (MR) techniques are capable of producing high-resolution three-dimensional anatomic images. 4D flow allows for the gated acquisition of all three velocity components throughout an entire three-dimensional space.[1] This technique has previously been used to image flow patterns in the thoracic aorta as well as the cerebral vasculature.[2-5] The acquisition strategy is described in Fig 1. Gated electrocardiogram (EKG) data acquired over multiple heartbeats is retrospectively reconstructed into 20 segments of the cardiac cycle. The study was performed on a 1.5 T magnet with an eight-channel body coil. For analysis, the data is imported into a three-dimensional visualization software package (EnSight Version 8.0.7; CEI Inc, Apex, NC), and streamlines are used to visualize flow patterns. Streamlines are imaginary lines aligned with the local velocity vector field at a specific point in time. Velocities can be measured by placing two-dimensional planes throughout the data set. These planes are exported from EnSight and quantified using a proprietary software program (Aspire2; Stanford University, Stanford, Calif). Mean velocities are calculated by averaging velocities across the vessel lumen at each point in the cardiac cycle. By allowing for directionality and characterization of flow at any point inside the lumen of the endograft, the technique can aid in the characterization of endoleaks. One limitation of phase contrast for the visualization of flow is the need to select the range of velocities encoded. This sets the upper limit of velocities that can be imaged, but the higher the upper limit, the lower the technique's sensitivity is to slower velocities. Of note, this technique does not require the administration of gadolinium based contrast material, although this acquisition was preformed after a traditional MRA. At this time, the technique is available only at certain academic centers, but it is expected to become more widely available as the acquisition is added as a basic component to MR scanners and with increased access to the required software.

CASE REPORT

An 80-year-old man with hypertension and coronary artery disease presented with exertional dyspnea and increasing back pain. He was found to have a 7.0 cm infrarenal abdominal aneurysm and underwent endovascular aneurysm repair in 2000 with prompt resolution of his back pain. His postoperative course was characterized by a persisting endoleak with three secondary procedures, including a proximal extender cuff at 6 months, coil embolization of the inferior mesenteric and lumbar arteries at 1 year, and conversion to a suprarenal aorto-uni-iliac endograft and femoro-femoral bypass at three years (Fig 2). The proximal endoleak persisted and was thought to be a type II endoleak from high lumbar arteries near the aortic neck. Because of an elevated creatinine, imaging was performed with gadolinium enhanced MRA (Fig 3) and later with non-contrast computed tomography (CT) and Duplex ultrasound. The patient remained asymptomatic but the aneurysm had enlarged to 8.0 cm, 6.5 years after the initial endovascular aneurysm repair.

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Competition of interest: none.

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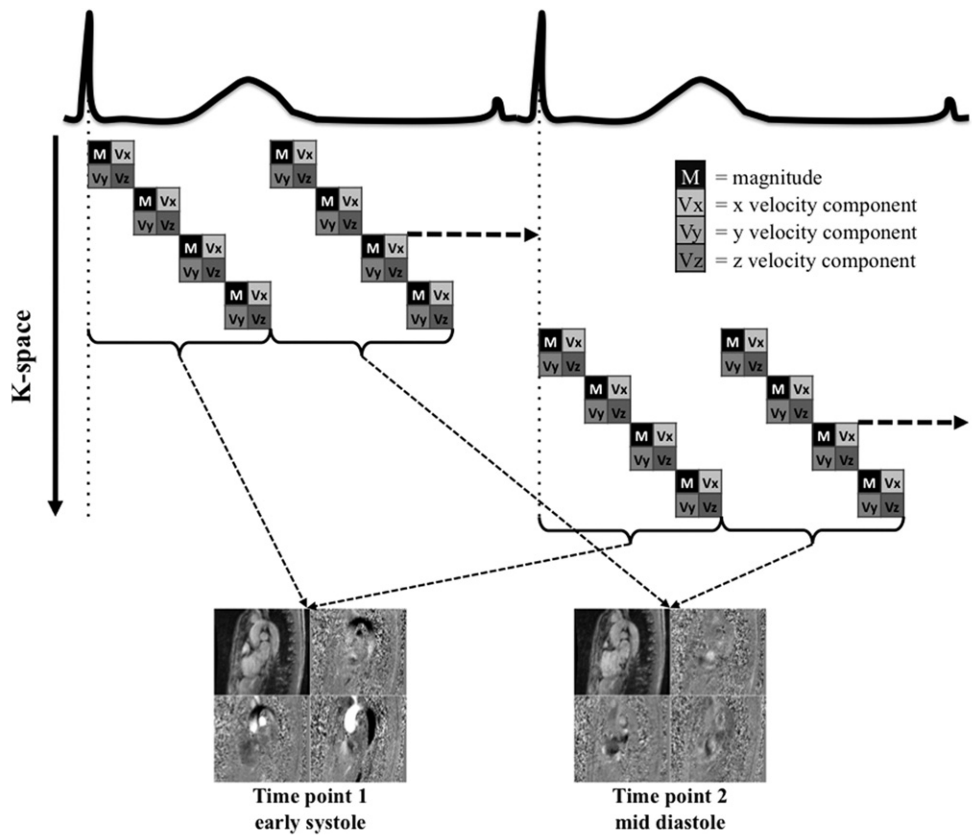

Fig 1. Time-resolved three-dimensional phase-contrast magnetic resonance imaging (MRI) or 4D flow acquisition. Phase contrast MRI allows for the acquisition of velocity encoded images by applying bipolar gradients. For each phase encode (*represented by a large square*), a reference image and three velocity components are acquired. In this acquisition, four phase encodes were acquired and then repeated throughout each cardiac cycle determining the temporal resolution (*65 ms in this case*). During the next cardiac cycle, four different phase encodes were acquired until the entirety of k-space was acquired. Data is grouped based on when it was acquired in the cardiac cycle to reconstruct a temporally resolved data set (Adapted from Markl et al 2003).[1]

At that time a 4D flow scan was performed showing blood flow entering the aneurysm sac through a type I endoleak. This is shown in Figs 3 and 4, where streamlines are seen entering the aneurysm at the proximal portion of the endograft. A plane placed at the inlet of the endoleak shows antegrade flow with a maximum velocity of 7 cm/s into the aneurysm defining this as a type 1 endoleak (Fig 5). Flow through lumbar arteries could not be identified on the 4D flow images. The patient declined recommended open aortic aneurysm repair. Six months later, 7 years after his initial endovascular repair, the aneurysm had enlarged to 8.7 cm and the persisting type I endoleak was again identified with Duplex ultrasound. The patient consented to surgery and underwent modified open aneurysm repair with surgical exposure of the aortic neck and external wrapping of the neck with a Dacron band to reduce its diameter and seal the proximal type I endoleak. The aneurysm was then opened and absence of a type I endoleak was directly confirmed; several small lumbar artery orifices were suture ligated. The aneurysm was then sutured closed with reduction of aneurysm diameter to 4.5 cm. Aortic cross-clamping was not required, and the endograft remained in place. The patient recovered uneventfully and postoperative imaging confirmed absence of endoleak.

DISCUSSION

Endoleaks are a common finding following EVAR,[6] but not all endoleaks require treatment. While attachment site endoleaks (type I) and endoleaks arising from fabric defects or modular component junctions (type III) require urgent treatment, retrograde flow in the aneurysm sac from aortic branches (type II endoleaks) are usually treated conservatively, unless there is significant aneurysm enlargement. Thus, it is imperative to determine the type and source of the endoleak.[6-10]

Contrast enhanced CT scanning has been the method of choice for following patients post-EVAR. However, since CTA is a pooled imaging technique and characterizes endoleaks in a static picture, it is not able to visualize the directionality of flow. Duplex ultrasound can provide real time information of endoleak flow velocity and direction and is commonly used to evaluate

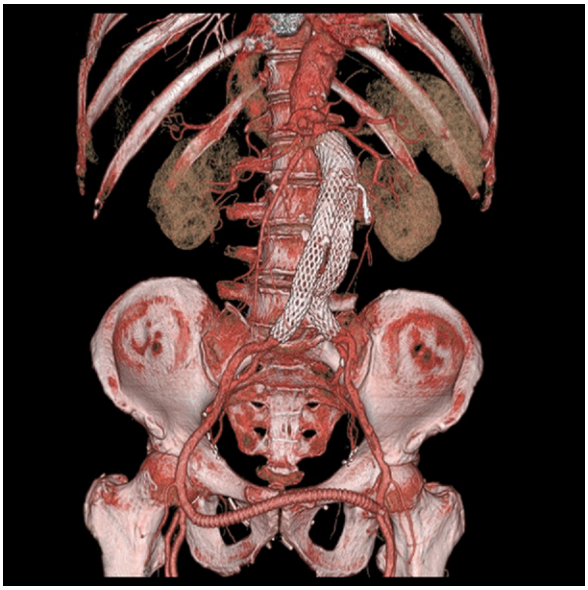

Fig 2. Volume rendered computed tomography angiography depicting the location of the endografts as well as the femoral-femoral bypass.

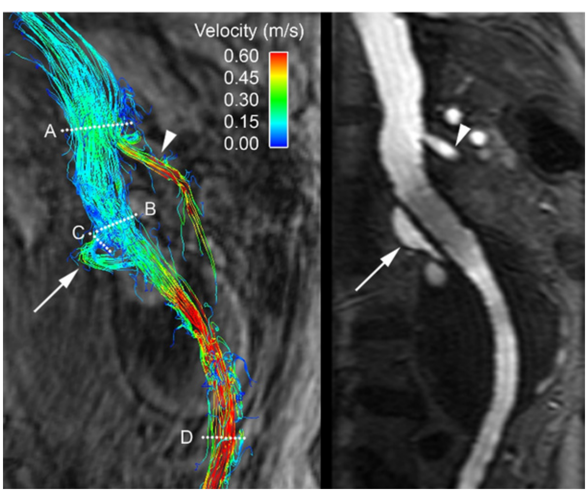

Fig 3. 4D flow acquisition depicting blood flow through the endograft at peak systole (*left*). Speed is depicted by the color of the streamlines. The arrowhead points to the superior mesenteric artery, while the arrow points to flow entering the type I endoleak. Planes used for calculation of mean velocities are labeled (*planes A-D*). Streamlines continue only into the right iliac artery as there is a limb occluder in original left graft limb. MRA curved-planar reformation through the abdominal aorta and right iliac graft shows corresponding contrast in the proximal neck of the aneurysm supporting the diagnosis of a type I endoleak (*right*).

patients following endovascular treatment. However, it has limitations in visualizing the entire aneurysm and is limited by the capabilities of the ultrasonographer.[11] Recently, it has been shown that MRA evaluation of

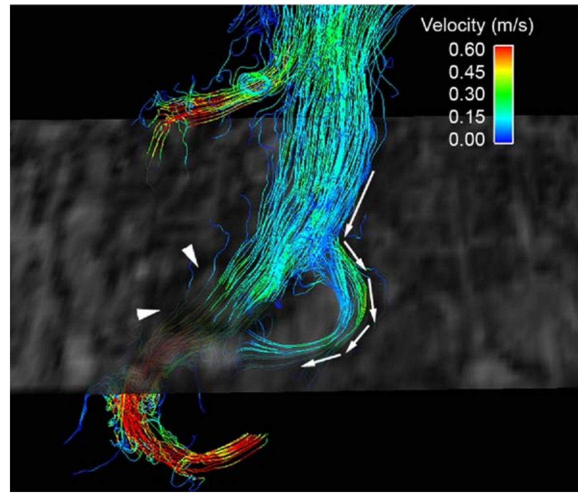

Fig 4. Oblique sagittal view of 4D flow streamlines depicting flow into the aneurysm sac. A semitransparent axial plane through the proximal neck of aneurysm shows contrast outside of the vessel lumen. Streamlines exit the vessel and enter the aneurysm sac posteriorly (*arrows*). Streamlines continue through the patent endograft lumen (*arrowheads*).

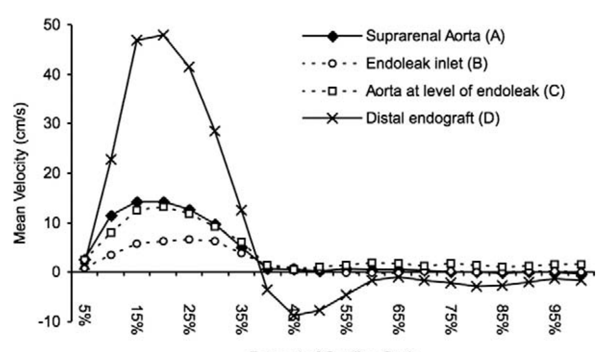

Fig 5. Chart of mean velocities across the aortic lumen and the inlet of the proximal type I endoleak as described in Fig 3. Suprarenal aortic velocity profiles are similar to the proximal portion of the endograft, 14 and 13 cm/s, respectively (*planes A and C*). There is net flow into the inlet of the endoleak with a maximum velocity of 7 cm/s, and there is no retrograde flow during diastole (*plane B*). In the distal graft (*plane D*), velocities increase significantly to a maximum of 48 cm/s due to tapering, and there is a significant amount of retrograde flow in early diastole due to the decreased distensibility compared with the native vessel wall.

endoleaks is more sensitive than CTA,[12] and time-resolved contrast enhanced MRA allows for the better definition of an endoleak source due to its ability to show directionality of blood flow.[13] One must remember that patients with stainless steel stents and coils are not able to be evaluated completely utilizing MRI due to distortion artifacts in the area of interest.[14] Also, all stents will have some amount of signal loss due to "radiofrequency caging" effects, but nitinol stents do not heat or travel in the lumen during an MRI.[15] The majority of currently available endografts utilize nitinol stents and thus have minimal artifacts when imaged with MRI.[16]

In the patient described in this report, the 4D flow technique helped characterize the type 1 endoleak. MRA findings showed multiple lumbar arteries entering the aneurysm sac, which led initially to the diagnosis of a type II endoleak. With the velocity information provided by the 4D flow acquisition, flow was clearly seen entering into the proximal portion of the aneurysm from the attachment site, thus, defining this as a type 1 endoleak. The combination of the three-dimensional anatomic and velocity information allowed the 4D flow method to correctly characterize this endoleak.

Visualization of velocity profiles will become more important in the description and characterization of endoleaks. Directional Doppler waveforms have been associated with clinical outcomes following EVAR. For example, a to/fro waveform has been associated with spontaneous sealing of type II endoleaks while a monophasic or biphasic waveform is associated with persistence of the endoleak.[17] Also, understanding endoleak flow velocities in the aneurysm sac may help determine the risk of rupture. The rate of flow into the aneurysm sac may be correlated with endolumenal pressure and tension on the aneurysm wall. Imaging of blood flow velocities and wall movement may also help further the understanding of endotension, the situation where there is no evidence of an endoleak in the presence of an enlarging excluded aneurysm. The etiology of endotension is debated and the appropriate treatment remains controversial.[18,19]

In patients with renal disease, such as the one discussed, CTAs with iodinated contrast is contra-indicated because of the associated contrast induced nephropathy.[20] More recently, MRAs have been limited in the same population of patients because of the incidence of nephrogenic systemic fibrosis, a newly described disease that occurs only in renal failure patients who have received gadolinium contrast.[21] Since the 4D flow technique can be performed without the administration of gadolinium, it may be a clinical alternative to MR and CT angiograms in patients with renal failure.[2]

CONCLUSION

CTA, conventional MRA, and Duplex ultrasound have been used to identify and characterize endoleaks following EVAR. We have identified a new imaging modality for evaluating endoleaks: time-resolved three-dimensional phase contrast MR or 4D flow. The 4D flow technique combines the three-dimensional resolution of cross-sectional imaging with the temporally resolved velocity data of Doppler ultrasound. This combination allows for effective imaging of flow patterns in and around endovascular stent grafts, specifically aiding in the differentiation of type I and type II endoleaks using flow direction and magnitude. As this type of scan becomes more widely available and scan times are decreased, this technique may aid in the work-up of post-EVAR patients, especially in patients with renal failure.

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