Novel Dynamic Four-Dimensional CT Angiography Revealing 2-Type Motions of Cerebral Arteries

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Background and Purpose—We developed a novel dynamic 4-dimensional CT angiography to accurately evaluate dynamics in cerebral aneurysm.

Methods—Dynamic 4-dimensional CT angiography achieved high-resolution 3-dimensional imaging with temporal resolution in a beating heart using dynamic scanning data sets reconstructed with a retrospective simulated R-R interval reconstruction algorithm.

Results—Movie artifacts disappeared on dynamic 4-dimensional CT angiography movies of 2 kinds of stationary phantoms (titanium clips and dry bone). In the virtual pulsating aneurysm model, pulsation on the dynamic 4-dimensional CT angiography movie resembled actual movement in terms of pulsation size. In a clinical study, dynamic 4-dimensional CT angiography showed 2-type motions: pulsation and anatomic positional changes of the cerebral artery.

Conclusions—This newly developed 4-dimensional visualizing technique may deliver some clues to clarify the pathophysiology of cerebral aneurysms. (Stroke. 2011;42:00-00.)

Key Words: aneurysm ■ CT angiography ■ hemodynamics

H emodynamic stress is 1 factor contributing to the initiation of cerebral aneurysm and the rupture process, but simple determination of aneurysm size and location never accounts for hemodynamic forces or the ability of aneurysms to withstand them.1 We recently succeeded in visualizing the dynamics of cerebral aneurysms with electrocardiogram-gated 4-dimensional CT angiography (4D-CTA) in clinical settings.2 However, application of electrocardiogram-gated 4D-CTA to assess the dynamics of aneurysm wall has shown certain limitations, the most significant of which was various visual artifacts.3,4 We therefore developed a novel 4-dimensional visualizing technique, dynamic 4D-CTA (DFA), to more accurately evaluate the dynamics of motion in cerebral aneurysms.

Methods
DFA movies were made using dynamic scanning data sets reconstructed with a retrospective simulated R-R interval reconstruction algorithm. The accuracy of DFA was evaluated using stationary and pulsating phantoms and in 4 patients with unruptured cerebral aneurysms (available at http://stroke.ahajournals.org).

Results
Stationary Phantom
Movie artifacts on DFA completely disappeared in a titanium clip phantom (Movie S1) and were much fewer in a dry bone phantom than electrocardiogram-gated 4D-CTA (Movie S2): the CT value was approximately 3000 and 500 Hounsfield units, respectively.

Pulsating Phantom
A DFA movie was constructed from 10 phases in 1 cardiac cycle and showed pulsations resembling actual movement of the virtual pulsating aneurysm model (approximately 250 to 300 Hounsfield units; Movie S3). The phase of 3-dimensional CT angiographic images was in the order of absolute time from the newest R wave (Figure 1A). Maximum surface area and volume were observed at the same time, at approximately the 25% R-R interval (Figure 1B). The size of pulsatile motion of the aneurysmal dome in an axial direction was approximately 0.7 mm, close to the real size of the virtual pulsating aneurysm model (Figure 1C).

Clinical DFA
The DFA movie appeared to depict real movement of arteries, not artifacts (Movie S4). Two types of movements were observed in intracranial arteries: pulsation of the artery itself, probably resulting from contraction and extension of the arterial wall during the cardiac cycle, and motion associated with anatomic positional change (ie, same amplitude for all regions; Movie S5). To clarify contraction and extension of

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arterial wall, changes in middle cerebral artery (MCA) volume/average MCA volume were analyzed (Figure 2A). In addition, to reveal the relationship between MCA volume variation and flow velocity in the MCA, the approximate curve of MCA volume variation was overlapped with flow velocity as determined by transcranial Doppler ultrasonography of the MCA. Peak MCA volume appeared after maximum flow velocity in the MCA (Figure 2B). Next, positional analysis was performed by the overlap imaging method of diastolic-phase (red) and systolic-phase (blue) DFA images (Figure 3A). The overlap image from an anterior view showed the artery as nearly red and a posterior view as blue (Figure 3B), indicating that the artery moved from an anterior position in the diastolic phase to posteriorly in the systolic phase. Intracranial arteries of both the anterior and posterior circulation moved similarly in another case (Figure 3C). However, occipital bone did not move like arteries (Figure 3D).

**Discussion**

Recent reports have revealed the usefulness of 4D-CTA in evaluating cerebral aneurysms. To precisely evaluate the dynamics in cerebral aneurysm walls, some new techniques including electrocardiogram-gated 4D-CTA and the dynamic multiscan technique have been developed and shown improvements in the image quality. However, certain artifacts remain problematic although using these techniques (Movie S6). We believe that DFA is the best method for visualizing the dynamics of cerebral aneurysms without movie artifacts.
Yaghmai et al. reported that artifacts on 4D-CTA result from a lack of cone beam correction. We supposed that start angles of the gantry might give rise to these artifacts even using dynamic multiscan techniques. Half reconstruction corresponding to gantry rotation time is the most important technique to obtain high temporal resolution for image reconstruction. In addition, use of the same start angle for the detector is necessary to reduce movie artifacts during dy-

Figure 2. DFA visualizing in vivo pulsation of cerebral artery. A, MCA volume (VMCA) changes/mean VMCA; (B) relationship between VMCA changes and MCA flow velocity during a cardiac cycle.

Figure 3. DFA visualizing in vivo positional changes in cerebral artery. A, Diastolic-phase images are expressed in red and contraction-phase images in blue; (B) the overlap image from an anterior view shows artery as nearly red and the posterior view as blue; (C) arteries of both the anterior (lower) and posterior (upper) circulation move in a similar way; (D) occipital bone shows no movement.
namic scanning. Moreover, the temporal dimension in electrocardiogram-gated 4D-CTA is the average order of regular intervals within the R-R interval, whereas DFA uses a rearranged temporal order during the simulated R-R interval. To adopt these techniques, a simulated R-R interval reconstruction algorithm allows the acquisition of higher frame rates in 4D-CT movies without movie artifacts.

In a clinical setting, inconstant CT values of vascular enhancement also cause movie artifacts. We used a variable injection method to make variation of CT values in intracranial arteries on reconstruction images ≤25 Hounsfield units in all phases during the simulated R-R interval. As a result, clinical DFA provided high-quality movies without artifacts, revealing for the first time real 2-type movements of intracranial arteries.

DFA may determine the accurate amplitude of aneurysm wall pulsation, which would be related with the aneurysm wall fragility and the rupture process of cerebral aneurysms. Further studies may prove clinical usefulness of DFA such as identification of aneurysms with a high risk of rupture.

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**Disclosures**


**References**

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Supplemental Methods

Dynamic Four-Dimensional (4D) Computed Tomography (CT) Angiography (DFA)

A 64-detector multi-slice Aquilion CT scanner (Toshiba Medical Systems Corporation, Japan) was used to obtain dynamic scanning data in both experimental studies and clinical examinations. We applied DFA support software version 4.1 (Toshiba Medical Systems Corporation, Japan) for reconstructing DFA images. The dynamic scan technique used rapid and continuous image acquisition without table movement. Imaging was performed with a gantry rotation time of 0.4 s and a slice thickness of 0.5 mm with an effective scan width of 32 mm (64 × 0.5 mm). Tube current and voltage were set to 50 mA and 120 kV. DFA continuously scanned the stationary phantoms and virtual pulsating aneurysm model (VPAM) for 7.2 s and clinical subjects for 10 s while recording electrocardiograms (ECGs) to match acquisition to specific phases of the cardiac cycle. Source data image reconstructions were performed with 0.5-mm thickness. Before downloading reconstruction CT images to a visualization workstation (ZIO M900 Quadra; Amin, Tokyo, Japan), quantum noise was removed on the CT scanner computer. DFA included a new concept of time with a retrospective simulated R-R interval reconstruction algorithm that involved the rearrangement in absolute temporal order from the R wave (Figure S1). A collateral number was calculated on the computer attached to the Aquilion CT scanner, and the collateral number order meant the time interval between the newest R wave and the end of each scanning time. After rearrangement according to the collateral number and the CT series number, each 3D-CTA image was outputted as a JPEG. DFA movies were made using these JPEG files in relative temporal order.

ECG-Gated 4D-CT Angiography (CTA)
ECG-gated 4D-CTA was performed in the experimental studies using the stationary and pulsating phantoms to evaluate the artifacts on 4D-CT movies. Detailed description of this technique was reported previously.¹

**Stationary and Pulsating Phantoms**

A titanium clip (Yasargil, model FT764T; Aesculap, San Francisco, CA) with a CT value of about 3000 Hounsfield units (HU) and a dry bone phantom with a CT value of about 500 HU were employed as stationary phantoms. The stationary phantom was placed at the center of the gantry. The VPAM with a 5-mm diameter lumen and a 5-mm aneurysm dome at the side wall was made from latex and connected to a pulsation pump, which provided pressure at a pulsatile frequency of 62 beats/min. Pulsation amplitude of the dome was 0.7 mm in diameter. The VPAM was filled using contrast material diluted 30× with saline to adjust the CT value to about 250-300 HU on the axial CT image reconstructed using the FC41 reconstruction formula (Figure S2). For quantitative analysis, surface area and volume of the VPAM at each phase were measured using INTAGE Volume Editor software (KGT, Tokyo, Japan).

**Clinical DFA**

DFA was performed in 4 patients with unruptured cerebral aneurysms at NHO Mie Chuo Medical Center (Table S1). Contrast medium injection was performed using a 100-ml dose of Omnipaque 370 nonionic contrast medium (Daiichi Pharmaceutical, Tokyo, Japan) delivered into an antecubital vein. To maintain a stable intra-arterial CT value during dynamic scanning, Dual Shot GX (Nemoto Kyorindo, Tokyo, Japan) was used in the variable injection method. Using this method, initial injection rate was determined based on patient body weight and then the injection rate was decreased to half the initial rate. At each phase when DFA was obtained, a CT value was measured in all reconstruction images in the DFA movie. All DFA movies were made using adequate reconstruction images, for which the variation in CT value was kept <25 HU (Figure S3). To analyze arterial pulsation, volume of the sphenoidal (M1) segment of middle cerebral arteries (MCAs) was measured in 54 phases of 8 MCAs.
Supplemental Table

**Table S1.** Summary of clinical DFA studies in patients with unruptured cerebral aneurysm.

<table>
<thead>
<tr>
<th>Case</th>
<th>Location</th>
<th>Size (mm)</th>
<th>Mean R-R interval (sec)</th>
<th>Phase number during one cardiac cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ICA</td>
<td>6.5</td>
<td>0.812</td>
<td>7</td>
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<tr>
<td>2</td>
<td>ICA</td>
<td>11.0</td>
<td>0.938</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>MCA</td>
<td>5.2</td>
<td>0.953</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>VA</td>
<td>4.8</td>
<td>0.820</td>
<td>7</td>
</tr>
</tbody>
</table>

ICA, internal carotid artery; MCA, middle cerebral artery; VA, vertebral artery.
Supplemental Figures and Figure Legends

Figure S1

Schema of DFA showing the concept of the retrospective simulated R-R interval reconstruction algorithm.
The virtual pulsating aneurysm model (VPAM) that was made using a latex tube with a 5-mm diameter lumen and a 5-mm aneurysm dome on the side wall, circulating diluted contrast material via a pulsation pump (A). The VPAM placed at the center of the gantry (B) is affected by pressure wave with a pulsation frequency of 62 beats/min (C).
CT values in intracranial arteries or aneurysms are evaluated during image acquisition on all dynamic CT images per 1 second. All clinical DFA movies are made only using source CT images with CT value variation <25 HU (green square).
Supplemental References

Supplemental Movie Legends

**Movie S1.** The titanium clip on ECG-gated 4D-CTA movie (A) and DFA movie (B).

**Movie S2.** The dry bone phantom on ECG-gated 4D-CTA movie (A) and DFA movie (B).

**Movie S3.** DFA movie showing dynamics of the VPAM.

**Movie S4.** Clinical DFA movie showing the movement of intracranial arteries without artifacts, as demonstrated by disappearance of movement of the external ear.

**Movie S5.** Clinical DFA movie showing two kinds of movement of intracranial arteries: pulsation and anatomical positional changes of the artery.

**Movie S6.** Dynamic multiscan technique 4D-CTA movie (A) and DFA movie (B) of a dry bone phantom.
脳動脈の 2 種類の運動を捉える新しいダイナミック四次元 CT 血管造影法

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背景および目的：著者らは、脳動脈瘤の動態を正確に評価する、新しいダイナミック四次元 CT 血管造影法を開発した。

方法：ダイナミック四次元 CT 血管造影法では、後ろ向きにシミュレートした R-R 間隔による画像再構成アルゴリズムによって動的スキャンデータセットを再構成し、このデータセットを用いて、高分解能の三次元撮像と、拍動する心臓を捉える時間分解能を実現した。

結果：2 種類の静止ファントム（チタンクリップおよび乾燥骨）のダイナミック四次元 CT 血管造影動画像では、ムービーアーチファクトが消失した。拍動する動脈瘤の仮想モデルでは、動画上の拍動は、拍動の大きさの点で実際の運動に類似していた。臨床研究では本法により、脳動脈瘤の拍動と解剖学的位置変化という 2 種類の運動が示された。

結論：新たに開発されたこの四次元描出法によって、脳動脈瘤の病態生理を解明する手がかりが得られる可能性がある。

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