MAJOR PAPER

Feasibility of a Curvature-based Enhanced Display System for Detecting Cerebral Aneurysms in MR Angiography

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Purpose: To assess the feasibility of a curvature-based enhanced display system for detecting cerebral aneurysms in MR angiography.

Methods: MR angiography studies of 18 patients (eight male and 10 female, average age 65.7, age range 50 to 75 years old) with 23 known aneurysms were evaluated with a curvature-based display system. The two curvature features—the volumetric shape index and curvedness values—were calculated at each voxel. These were displayed independently on a workstation, overlaid on volume-rendered images. Two neuroradiologists evaluated the images for visibility and diagnosis of the cerebral aneurysms. The diagnostic results were compared with the original reports.

Results: The calculation time for each curvature index was 30 to 40 s for 120 to 140 slices of original MR angiography data. Shape index images emphasized smooth and round aneurysms more than aneurysms with irregular surfaces. Curvedness images revealed aneurysms well when the aneurysms had diameters that differed from those of the surrounding vessels. The computer-assisted-detection method detected 24 aneurysms, three of which were not pointed out in the initial report.

Conclusion: Our results show that the curvature-based display system we have developed is feasible and that it may help to detect small aneurysms that are prone to be overlooked in routine readings.

Keywords: *MR angiography, cerebral aneurysm, curvature, image analysis, computer-assisted detection*

Introduction

Detecting small cerebral aneurysms with MR angiography is a challenging task for both professional neuroradiologists and neurosurgeons alike. Okahara et al. reported that the detection sensitivity of cerebral aneurysms with MR angiography was 60–79%, with digital subtraction 3D angiography used as the standard of reference.¹ A high percentage of false negative aneurysms were simply overlooked. In an effort to reduce human error in the detection process, we have developed a curvature-based display system that displays volume-rendered images with overlaid curvature indices calculated

from MR angiography volume data. The purpose of this paper is to evaluate the feasibility of this method.

Material and Methods

1) Imaging and data collection

From our teaching files we collected retrospective MR angiography studies, each of which was known to include at least one cerebral aneurysm. MR angiography studies of 18 patients (eight male and 10 female, average age 65.7 years, ranging from 50 to 75 years old) with a total of 23 known aneurysms were evaluated by the curvature-based display system. All studies included radiological reports written by neuroradiologists at the time of the study. MR angiography was performed with a 1.5-

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Fig. 1. Curvature classes
(K: Gaussian curvature, H: Mean curvature)

tesla MR scanner (Magnetom Vision, Siemens, Erlangen, Germany). MR angiography was obtained with 3D time of flight sequences in a single slab with the following parameters: image slices: 120 to 140, thickness: 0.88 to 1.0 mm, TE/TR/FA = 7.0/39/20 or 6.5/39/20 or 5.4/30/15, matrix: 512×512 , and field of view: 200 mm.

2) Preprocessing

The original image data were transferred to the workstation (M900, ZIOSOFT, Tokyo, Japan) in DICOM format. Images were interpolated in the Z-axis, so the voxel sizes were $0.39 \times 0.39 \times 0.44$ – 0.50 .

3) Volumetric image analysis (curvature computation)

The original volume data were then transferred to another program to calculate curvature indices. Two curvature features—the volumetric shape index and the curvedness values²—were calculated at each voxel for the entire volume data. The shape index³ characterizes the topologic shape of the volume in the vicinity of the voxel. This index determines to which of the following five topologic

Fig. 2. Color scale

shapes a voxel belongs: pit, valley, saddle, ridge or peak. The shape index is normalized between 0 and 1. Voxels characterized as the pit shape have values around 0; valley, around 0.25; saddle, around 0.5; ridge, around 0.75; and peak, around 1.0, although the transition from one topologic shape to another occurs continuously (Fig. 1). The curvedness of a

particular voxel represents the magnitude of the effective curvature at the voxel, which is defined as the square root of the sum of the squared minimum and maximum curvatures at the voxel.⁴ Generally, points on a large sphere-like object have small curvedness values. Taken as a pair, the shape index and the curvedness specify the local second-order geometry.³ The information contained in the pair is formally equivalent either to the two principal curvatures or to the Gaussian and mean curvatures taken as a pair.

The curvature indices were calculated according to the following formulas.²⁻⁴

3D function of volume data: $f(x, y, z)$

Gaussian curvature:

$$K = \frac{1}{(f_x^2 + f_y^2 + f_z^2)^2} [f_x^2(f_{yy}f_{zz} - f_{yz}^2) + 2f_yf_z(f_{xy}f_{zx} - f_{xx}f_{yz}) + f_y^2(f_{zz}f_{xx} - f_{zx}^2) + 2f_zf_x(f_{yz}f_{xy} - f_{yy}f_{zx}) + f_z^2(f_{xx}f_{yy} - f_{xy}^2) + 2f_xf_y(f_{zx}f_{yz} - f_{zz}f_{xy})] \quad (A)$$

Mean curvature:

$$H = \frac{1}{2(f_x^2 + f_y^2 + f_z^2)^{3/2}} [f_x^2(f_{yy} + f_{zz}) - 2f_yf_zf_{yz} + f_y^2(f_{zz} + f_{xx}) - 2f_zf_xf_{zx} + f_z^2(f_{xx} + f_{yy}) - 2f_xf_yf_{xy}] \quad (B)$$

Principal curvatures k_1 (maximum), k_2 (minimum)

$$k_1 = H + \sqrt{H^2 - K} \quad (C)$$

$$k_2 = H - \sqrt{H^2 - K} \quad (D)$$

$$\text{Shape index: } S = \frac{1}{2} - \frac{1}{\pi} \arctan \frac{k_1 + k_2}{k_1 - k_2} \quad (E)$$

$$\text{Curvedness: } R = \frac{1}{2} \sqrt{k_1^2 + k_2^2} \quad (F)$$

For shape index and curvedness, two-color volume data sets were prepared for the curvature display so that each voxel had independent red, green, and blue color components. Color scales were optimized for each curvature index (Fig. 2).

4) Display

The calculated volume data were returned to the display program with the RGB data for curvature indices. The volume-rendered images of the cerebral arteries, with overlapping color RGB data for the calculated curvature indices, were displayed on a workstation. Two neuroradiologists interpreted the images without knowledge of the original radiological reports. The two neuroradiologists reached a consensus on their interpretations of the images through discussion; any initial inconsistencies were carefully reexamined and resolved. The interpretation of the images as well as the number

and location of cerebral aneurysms were compared with the original radiological reports.

Results

The time required to calculate each curvature index on a PC workstation (equipped with a Xeon 2.2 GHz processor) was 30 to 40 s for 120 to 140 slices of the original MR angiography data. Manual adjustment of the window level and transparency level was necessary to optimize the visualization of the volume-rendered images.

On the shape index images, smooth round aneurysms were the best to be emphasized (Fig. 3). Aneurysms with irregular surfaces, such as mixed contours of concave and convex surfaces, resulted in mosaic pattern contrast (Fig. 4); therefore, such aneurysms were not emphasized as well as smooth round aneurysms. Moreover, large aneurysms with irregular intra-aneurysmal flow were poorly visualized owing to the poor delineation of the volume-rendered images themselves (Fig. 5). Other highlighted structures in the shape index images included vessel wall irregularities, outer aspects of hairpin curves, and small bumps in the vessel walls.

On the curvedness images, visualization of overlapping vessels and aneurysms (Figs. 3 and 4) was superior to that of normal gray-scale volume-rendered images. These resulted in accentuation of larger-diameter aneurysms against the smaller-diameter cerebral vessels.

In summary, use of this display system resulted in the identification of 24 aneurysms among the 18 MR angiography studies, with six patients being identified with two aneurysms each (Table). All aneurysms identified in the initial radiological reports were correctly detected; however, the initial radiological reports of MR angiography identified only 21 cerebral aneurysms. The three cerebral aneurysms that the initial radiological reports failed to identify were all smaller secondary aneurysms in the presence of a larger primary aneurysm; two of these were identified with conventional angiography, while the last did not undergo a conventional angiography study. One was a low-height, 3-mm aneurysm at the left posterior cerebral artery with a large posterior communicating artery due to occlusion of the left internal carotid artery in the presence of another larger aneurysm at the basilar tip (Fig. 6). The second was a 2-mm aneurysm at the distal anterior cerebral artery in the presence of another larger aneurysm at the anterior communicating artery (Fig. 7). The last was a 2.5-mm ICA-posterior communicating artery aneurysm in the presence of another larger

Fig. 3. MR angiography of a 70-year-old female with a 4-mm aneurysm in the right ICA bifurcation (vertical arrows) and a 2.5-mm aneurysm in the left MCA bifurcation (diagonal arrows) viewed from above. Smooth round aneurysms such as these are best enhanced in shape index images.

a) Volume-rendered image, b) Shape index image, c) Curvedness image

Fig. 4. MR angiography of a 50-year-old male with a large aneurysm (arrows) in the cavernous portion of the right internal carotid artery viewed from above. Irregularity of the aneurysmal surface marks the mosaic pattern seen in the shape index image.

a) Volume-rendered image, b) Shape index image, c) Curvedness image

Fig. 5. MR angiography of a 58-year-old female with a large aneurysm in the left cavernous sinus viewed from above. Signal loss due to slow and turbulent flow renders the contour of the aneurysm incomplete. Neither of the curvature images reveals the aneurysmal contour because they are overlaid in the volume-rendered image.

a) Volume-rendered image, b) Shape index image, c) Curvedness image

Table. List of patients with number of aneurysms in the original report and number of aneurysms detected on curvature-based display

Patient number	Sex	Age	Number of aneurysms detected in original report	Number of aneurysms detected on curvature-based enhanced display	Location and size of aneurysm
1	Male	65	1	1	Left distal ACA (3 mm)
2	Male	75	1	1	Basilar tip (10 mm)
3	Male	66	1	1	Right PCA (30 mm)
4	Male	50	1	1	Right ICA (20 mm)
5	Female	59	1	2	Basilar tip (3.5 mm), left PCA (3 mm)
6	Female	69	1	2	Right ACA A1-2 portion (4 mm), right ACA A2-3 portion (2 mm)
7	Female	66	2	2	Right MCA (10 mm), basilar (4 mm)
8	Male	74	1	1	Right MCA (6 mm)
9	Male	70	2	2	Right ICA (4 mm), left MCA (2.5 mm)
10	Female	70	1	1	Right PICA (5 mm)
11	Female	66	2	2	Right MCA (2.5 mm), left ICA (3 mm)
12	Male	62	1	1	Left MCA (6 mm)
13	Female	70	1	2	Left ICPC (8 mm), right ICPC (2.5 mm)
14	Female	75	1	1	BA fenestration (30 mm)
15	Female	58	1	1	Left ICA cavernous portion (26 mm)
16	Male	60	1	1	Right distal ACA (15 mm)
17	Female	72	1	1	Right distal ACA (20 mm)
18	Female	55	1	1	Right ICA cavernous portion (18 mm)
Total number of aneurysms			21	24	

Abbreviations: ACA: anterior cerebral artery, MCA: middle cerebral artery, PCA: posterior cerebral artery, ICA: internal carotid artery, ICPC: bifurcation of internal carotid artery and posterior communicating artery

aneurysm in a similar location on the contralateral side. Overall, our evaluation with the curvature-based display system produced information supplemental to the initial radiology report in three of 18 studies (16.7%).

Discussion

We have shown that the curvature-based display system we have developed is feasible and that it may help to decrease human error in the detection of cerebral aneurysms on MR angiography. The computing times required for calculating the curvature indices were relatively short, so we believe this curvature-based display system may well be applicable to clinical practice. Moreover, some of the cases with small aneurysms indeed seem to be better depicted by this system than by conventional display methods.

The higher detection rate from evaluation with the curvature-based display system can be attributed to several factors. First, the calculated curvature indices may actually improve the visibility of the cerebral aneurysms. Second, evaluating the volume-rendered images on a 3D workstation

instead of conventional film may improve the visibility of the cerebral aneurysms. Last, the study design of first look versus second look as well as the forging of a consensus between the two radiologists likely improves rather than worsens the detection rate. The true validity of this display system cannot be evaluated, as this is only a retrospective study. However, we believe we have presented results sufficient to show that this is a prospective method for evaluating cerebral aneurysms.

The cerebral aneurysms that remained undetected in the initial reports were all less than 3 mm in diameter. Although aneurysms less than 3 mm in diameter can be detected with conventional display methods, it has been pointed out that 3 mm is a practical cutoff level for detection of cerebral aneurysms on MR angiography, as the detection rate is much lower for smaller aneurysms.¹ However, the same authors also point out that the rupture rate of aneurysms smaller than 3 mm cannot be neglected in cases of subarachnoid hemorrhages. The curvature-based display system may help to increase the low detection rates of these smaller cerebral aneurysms.

Fig. 6. MR angiography of a 59-year-old female viewed from above. There is a 4-mm aneurysm (vertical arrows) at the basilar tip and another low-height 3-mm aneurysm (horizontal arrows) at the first portion of the left posterior cerebral artery. Due to the low height of the 3-mm aneurysm, it is difficult to discern its presence in the gray-scale volume-rendered images.

a) Volume-rendered images (stereo view), **b)** Shape index images (stereo view)

Fig. 7. MR angiography of a 69-year-old female viewed from the left anterior. A 4-mm aneurysm (lower arrows) can be seen at the anterior communicating artery and another 2-mm aneurysm (upper arrows) can be seen at the distal anterior cerebral artery. Note that the 4-mm aneurysm is better depicted by curvedness images than shape index images due to surface irregularities. On the other hand, the 2-mm aneurysm is better depicted by shape index images because the diameter of the aneurysm is almost the same as that of the distal anterior cerebral arteries.

a) Volume-rendered image, **b)** Shape index image, **c)** Curvedness image

We acknowledge that the cost of screening cerebral aneurysms in the general population is not supported by recent studies.^{5,6} Computer-assisted detection in general, however, may reduce the total cost of screening by reducing the time required by neuroradiologists to interpret each examination. We also acknowledge that some studies have maintained that surgical intervention for non-ruptured single cerebral aneurysms does not benefit patient outcome due to the low risk of rupture and relatively high risk of complications from surgery.⁵⁻⁸ However, the risks of ruptures and the risks of intervention are not constant variables. The detection of a second aneurysm would be clinically important because multiple aneurysms in a patient represent a higher estimated risk for rupture.⁹⁻¹² As well, the second smaller aneurysm in the presence of a larger aneurysm is often overlooked.¹ The risk of intervention may also be lowered by new intervention techniques¹³ and by better patient management.¹⁴ We believe that low-cost screening for small cerebral aneurysms would have a significant clinical role in the near future.

Automated computer-aided detection is attractive because it has the potential to reduce the cost of screening while increasing diagnostic accuracy. Automated computer-aided detection systems using curvature indices have been developed for the colonic region and pulmonary regions.¹⁵⁻¹⁸ The next step in our project is to show the validity of this display system and to develop a fully automated computer-assisted detection system for cerebral aneurysms.

Conclusion

The curvature-based display system we have developed is feasible for displaying cerebral aneurysms on MR angiography. It enhances the visibility of cerebral aneurysms and may contribute to the detection of small aneurysms that are prone to be overlooked in routine readings.

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References

1. Okahara M, Kiyosue H, Yamashita M, et al. Diagnostic accuracy of magnetic resonance angiography for cerebral aneurysms in correlation with 3D-digital subtraction angiographic images: a study of 133 aneurysms. *Stroke* 2002; 33(7): 1803-1808.
2. Lohmann G. Volumetric Image Analysis. Chichester: John Wiley & Sons Ltd., 1998; 155-167.
3. Dorai C, Jain AK. COSMOS: a representation scheme for 3D free-form objects. *IEEE Trans Pattern Analysis Machine Intelligence* 1997; 19: 1115-1130.
4. Koenderink J, Doorn RC. Surface shape and curvature scales. *Image Vision Comput* 1992; 10: 557-565.
5. Wardlaw JM, White PM. The detection and management of unruptured intracranial aneurysms. *Brain* 2000; 123(Pt 2):205-221.
6. Baba Y, Takahashi M, Korogi Y. Cost-effectiveness of screening unruptured cerebral aneurysms in Japan. *Eur Radiol* 2000; 10(Suppl 3):S362-365.
7. International Study of Unruptured Intracranial Aneurysms Investigators. Unruptured intracranial aneurysms—risk of rupture and risks of surgical intervention. *N Engl J Med* 1998; 339(24):1725-1733.
8. Yoshimoto Y, Wakai S. Cost-effectiveness analysis of screening for asymptomatic, unruptured intracranial aneurysms. A mathematical model. *Stroke* 1999; 30(8):1621-1627.
9. Yasui N, Suzuki A, Nishimura H, Suzuki K, Abe T. Long-term follow-up study of unruptured intracranial aneurysms. *Neurosurgery* 1997; 40(6): 1155-1159.
10. Rinkel GJ, Djibuti M, Algra A, van Gijn J. Prevalence and risk of rupture of intracranial aneurysms: a systematic review. *Stroke* 1998; 29(1): 251-256.
11. de la Monte SM, Moore GW, Monk MA, Hutchins GM. Risk factors for the development and rupture of intracranial berry aneurysms. *Am J Med* 1985; 78:957-964.
12. Yasui N, Magarisawa S, Suzuki A, Nishimura H, Okudera T, Abe T. Subarachnoid hemorrhage caused by previously diagnosed, previously unruptured intracranial aneurysms: a retrospective analysis of 25 cases. *Neurosurgery* 1996; 39(6): 1096-1100; discussion 1100-1101.
13. Molyneux A, Kerr R, Stratton I, et al. International Subarachnoid Aneurysm Trial (ISAT) of neurosurgical clipping versus endovascular coiling in 2143 patients with ruptured intracranial aneurysms: a randomised trial. *Lancet* 2002; 360(9342): 1267-1274.
14. Johansson M, Cesarini KG, Contant CF, Persson L, Enblad P. Changes in intervention and outcome in elderly patients with subarachnoid hemorrhage.

- Stroke 2001; 32(12):2845–2949.
15. Summers RM, Selbie WS, Malley JD, et al. Polypoid lesions of airways: early experience with computer-assisted detection by using virtual bronchoscopy and surface curvature. *Radiology* 1998; 208(2):331–337.
 16. Summers RM, Beaulieu CF, Pusanik LM, et al. Automated polyp detector for CT colonography: feasibility study. *Radiology* 2000; 216(1):284–290.
 17. Mori K, Niki N, Moriyama N. Evaluation of computer-assisted diagnosis of small pulmonary nodules using contrast-enhanced dynamic helical CT. *Nippon Igaku Hoshasen Gakkai Zasshi* 2001; 61(1):17–24.
 18. Yoshida H, Masutani Y, MacEneaney P, Rubin DT, Dachman AH. Computerized detection of colonic polyps at CT colonography on the basis of volumetric features: pilot study. *Radiology* 2002; 222(2):327–336.
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