Hemodynamic Vascular Biomarkers for Initiation of Paraclinoid Internal Carotid Artery Aneurysms using Patient-specific Computational Fluid Dynamic Simulation Based on Magnetic Resonance Imaging

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Conflict of Interest

Haruo Isoda has received JSPS KAKENHI (Japan Society for the Promotion of Science, Grants-in-Aid for Scientific Research) (Grant Number 25293264).

Takafumi Kosugi is an employee of Renaissance of Technology Corporation, Hamamatsu, Japan.

The remaining authors declare that they have no conflict of interest.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent was obtained from all individual participants included in the study.

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ABSTRACT

Purpose

We performed computational fluid dynamics (CFD) for patients with and without paraclinoid internal carotid artery (ICA) aneurysms to evaluate the distribution of vascular biomarkers at the aneurysm initiation sites of the paraclinoid ICA.

Methods

This study included 35 patients who were followed up for aneurysms using 3D time of flight (TOF) magnetic resonance angiography (MRA) and 3D cine phase contrast MR imaging. Fifteen affected ICAs were included in Group A with the 15 unaffected contralateral ICAs in Group B. Thirty three out of 40 paraclinoid ICAs free of aneurysms and arteriosclerotic lesions were included in Group C. We deleted the aneurysms in Group A based on the 3D TOF MRA dataset. We performed CFD based on MR data set and obtained wall shear stress (WSS), its derivatives and streamlines. We qualitatively evaluated their distributions at and near the intracranial aneurysm initiation site among three groups. We also calculated and compared the normalized highest (nh-) WSS and nh-spatial WSS gradient (SWSSG) around the paraclinoid ICA among three groups.

Results

High WSS and SWSSG distribution were observed at and near the aneurysm initiation site in Group A. High WSS and SWSSG were also observed at similar locations in Group B and Group C. However, nh-WSS and nh-SWSSG were significantly higher in Group A than in Group C, and nh-SWSSG was significantly higher in Group A than in Group B.

Conclusion

Our findings indicated that nh-WSS and nh-SWSSG were good biomarkers for

aneurysm initiation in the paraclinoid ICA.

Keywords

- Intracranial Aneurysm
- Computational Fluid Dynamics
- Magnetic Resonance Imaging
- Wall Shear Stress

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INTRODUCTION

Intracranial aneurysm ruptures account for about 80% of the causes of non-traumatic subarachnoid hemorrhage, with a mortality rate of about 50% and a morbidity rate about 25% [1]. Aneurysms are prone to occur at vascular branches where blood flow collision occurs such as the circle of Willis [2, 3]. The internal carotid artery (ICA) siphon, however, has no such large vascular branches but is known to have side wall aneurysms [4]. This suggests that factors other than blood flow collision are involved in the initiation of aneurysms there.

Hemodynamics is involved in the initiation, growth, and rupture of intracranial aneurysms [2, 3, 5]. Computational fluid dynamics (CFD) is used to analyze hemodynamics and it more accurately reproduces the hemodynamics inside vessels when using patient-specific vascular geometry and boundary conditions. We can use rotational angiography, computed tomography angiography (CTA), and 3D TOF MRA to get patient-specific vascular geometry, but rotational angiography and CTA use contrast agents and have the risk of radiation exposure. We can obtain patient-specific boundary conditions with 3D cine phase-contrast (PC) MR imaging [6,7] and transcranial Doppler [8]. But the latter is unable to obtain data outside of a part of the middle cerebral artery making it difficult to obtain the volume flow rate (VFR) for any desired blood vessels. 3D cine PC MR imaging with analysis software [9], however, is capable of obtaining VFR in one cardiac cycle in any blood vessel with the benefit of being non-invasive. So a combination of 3D TOF MR angiography for the vascular geometry and 3D cine PC MR imaging for boundary conditions was thought to be the best technique for accuracy and patient comfort.

Wall shear stress (WSS) [5], which is the friction force working in parallel to the endothelial cells, as well as its derivatives, namely spatial WSS gradient

(SWSSG) [3], oscillatory shear index (OSI) [10], gradient oscillatory number (GON) [11], and aneurysm formation index (AFI) [12] are garnering attention as vascular biomarkers thought to be involved in the initiation, growth, and rupture of intracranial aneurysms. High WSS and SWSSG [3, 13-15], and high WSS and GON [16] have been noted at aneurysm initiation sites, however there are no studies that have made a quantitative evaluation as far as we know. A quantitative evaluation would allow us to establish objective biomarkers for aneurysm initiation. We focused on the paraclinoid segments [17] of ICA (paraclinoid ICA) prone to initiation of intracranial aneurysms. We hypothesized that aneurysms occur locally from the sites where biomarkers are highest and that an objective threshold could be established.

The objective of this study was to qualitatively and quantitatively evaluate the distribution of vascular biomarkers at sites at which side wall aneurysms of the paraclinoid ICA occur by using patient-specific CFD analysis based on MR data.

METHODS

Subjects

This study obtained the approval of the Institutional Review Boards of our institutions and informed consent was obtained from all subjects. The subjects were 56 patients with intracranial aneurysms who had been followed up with 3D TOF MR angiography and 3D cine PC MR imaging between 2007 and 2013 at two joint study facilities. These aneurysms were evaluated by a neuroradiologist (HI) with more than 20 years' experience. Patients were divided into two groups, 25 with aneurysms in the paraclinoid ICA and 31 (62 ICAs) with aneurysms at other locations. Among the patients with aneurysms in the ICA, we excluded 10 patients including a large aneurysm neck size (of >6 mm), for which it was difficult for us to reproduce

pre-aneurysmal geometry, cases where there was only MR imaging after coil embolization, and cases where marked arteriosclerotic changes were visible. From the other group, 29 large ICAs with arteriosclerotic changes were excluded from the analysis. Our analysis included 15 patients with 15 affected aneurysms in the paraclinoid ICA in Group A (age 26-79, mean 54.8, male:female = 3:12), 15 healthy ICAs (i.e., contralateral healthy side of the ICA aneurysm) in Group B, and 33 ICAs free of arteriosclerotic lesions of 20 patients with aneurysms outside the ICAs in Group C (age 42-81, mean 66.5, male:female = 10:10). Flow chart showing the study population and patient selection is shown in Fig 1. Patient demographics in Group A and B, and C and aneurysm locations in Group C are shown in Table 1 and 2. In group A, the location of paraclinoid aneurysms along the ICA were medial (n = 9: average size, 4.5 mm; ranging from 3.2 mm to 5.8 mm), superior (n = 5: average size, 4.5mm; ranging from 3.7 mm to 5.0 mm), and lateral (n = 1: size, 5.1 mm), according to the segment definition by Rafiei et al [17].

Imaging scanner and Imaging Parameters

We used a 3T MR scanner and 8ch neurovascular array coil or a 1.5T MR scanner and 8ch neurovascular array coil. The 1.5T MR scanner was used only for 4 patients with ICA aneurysms.

The imaging parameters of 3D TOF MRA for the 3T MR scanner were as follows: repetition time (TR), 26 ms; echo time (TE), 3.1 ms; flip angle, 20 degrees; field of view (FOV), 192 x 192 x 102 mm^3; matrix size, 512 x 192 x 204 (512 x 512 x 176 with zero fill interpolation); band width, 122 Hz/pixel; acquisition time, 5 min 39 s. The imaging parameters of 3D cine PC MR imaging were as follows: TR, 5.3 ms; TE, 2.4 ms; flip angle, 15 degrees; FOV, 160 x 160 x 32 mm^3; matrix size, 160 x

60 x 32 (256 x 256 x 64 with zero fill interpolation); band width, 488 Hz/pixel; views per segment, 4; No. of phases, 20; velocity encoding, 120 cm/s; acquisition time, 9 min 36 s.

The imaging parameters of 3D TOF MRA for the 1.5T MR scanner were as follows: TR, 30 ms; TE, 2.6 ms; flip angle, 15 degrees; FOV, 200x200x105 mm^3; matrix size, 320 x 224 x 176 (512 x 512 x 176 with zero fill interpolation); band width, 122 Hz/pixel; acquisition time, 4 min 48 s. The imaging parameters of 3D cine PC MR imaging were as follows: TR, 9.0 ms; TE, 3.0 ms; flip angle, 15 degrees; FOV, 160 x 160 x 32 mm^3; matrix size, 160 x 160 x 40 (256 x 256 x 40 with zero fill interpolation); band width, 488 Hz/pixel; views per segment, 4; No. of phases, 20; velocity encoding, 100 cm/s; acquisition time, 6 min 58 s.

Creating the Vascular Geometry and Obtaining the Boundary Conditions

We performed segmentation of the vascular structure from 3D TOF MRA data by the region growing method with reference to maximum intensity projection (MIP) images of 3D TOF MRA and created vascular geometries by the marching cube method [7] using blood flow analysis software (Flova; Renaissance technology corporation, Hamamatsu, Japan). The created blood vessels ranged from the ICA petrous segment to the anterior cerebral artery A1 segment and middle cerebral artery M1 segment. We retained the posterior communicating artery, the ophthalmic artery and the anterior choroidal artery when they could be clearly segmented by region growing method software using 3D TOF MRA data. We eventually deleted the ophthalmic artery in all patients. In addition, we removed the aneurysm with Flova in order to reproduce the geometry prior to aneurysm initiation (Fig 2 A, B). The neuroradiologist (HI) and a radiological technologist (TW) confirmed the

quality of the newly created vascular geometry. The vascular geometric data were then output in a stereolithography format as the vascular geometry for use in CFD analysis. We obtained the blood flow velocity vectors within the blood vessels after performing phase correction for phase images of 3D cine PC MR imaging [18] and also obtained temporal VFR during one cardiac cycle in each blood vessel [9], and used these VFRs as boundary conditions for the CFD analysis.

Mesh Creation

The vascular geometry was divided into an unstructured tetrahedral mesh with one edge length ranging from 0.1 to 0.3 mm using mesh creation software (ICEM CFD v14.5; ANSYS, Canonsburg, PA, USA). At the boundary layers adjoining the vascular walls, 4 prism layer meshes were created with the thickness of an outermost layer of 0.04 mm and a spreading rate of 1.2. In addition, the entrance region was extended 20 cm in order to create fully developed laminar flow in the ICA petrous segment. The inlet part was the ICA petrous segment, and the outlet parts were the anterior cerebral artery, middle cerebral artery, and the well-depicted posterior communicating artery and anterior choroidal artery.

CFD Analysis

We used CFD solver software (CFX version14.5; ANSYS, Canonsburg, Pennsylvania, USA). VFRs of vessels from 3D cine PC MRI data were used as inflow and outflow boundary conditions. Liquid was set as incompressible Newtonian fluid, density was set to 1054 kg/m^3 and viscosity was set to 3.8 mPa・s. We calculated ICA WSS using CFD with Newtonian model and with typical values of blood viscosity and density as WSSs of parent arteries obtained by Newtonian

and non-Newtonian models are similar [19]. The non-Newtonian effect, however, becomes most appreciated at very low shear rates because viscosity increases with decreasing shear rate. Vascular walls were rigid and no slip. Intervals of cardiac cycles were divided into 100 steps. Two cardiac cycles were simulated and we used the second cycle as the result. We calculated systolic WSS, systolic SWSSG, OSI, GON, AFI and systolic streamlines for color contour images.

Evaluation Method

The formulas for calculating WSS [5], SWSSG [3], OSI [10], GON [11], and AFI [12] are as follows:

$$\mathrm{WSS} = \mu \frac{dv}{dx}$$

$$\mathrm{SWSSG} = \frac{\mathrm{dWSS}}{\mathrm{dr}}$$

$$\mathrm{OSI} = \frac{1}{2}\left(1 - \frac{\int_0^t \overrightarrow{WSS} dt}{\int_0^t \left|\overrightarrow{\mathrm{WSS}}\right| dt}\right)$$

$$\mathrm{GON} = 1 - \frac{\left|\int_0^t \overrightarrow{SWSSG} dt\right|}{\int_0^t \left|\overrightarrow{SWSSG}\right| dt}$$

$$\mathrm{AFI} = \frac{\overrightarrow{WSS} \times \overrightarrow{WSS}ave}{|WSS| \times |WSSave|} (= cos\theta)$$

where μ is the viscosity, dv is the velocity, dx is the distance from the wall, dr is the distance in the flow direction, dt is time, $\mathrm{WSS}_{\mathrm{ave}}$ is the temporally-averaged WSS, and θ is the angle. We used systolic WSS, SWSSG and streamlines for the evaluation.

We performed qualitative and quantitative analyses as described below.

Qualitative Evaluation

The analysis results for the biomarkers WSS, SWSSG, OSI, GON, AFI, and the streamlines were visualized in contour image. In Group A, we evaluated the distribution of biomarkers at and near the aneurysm initiation site of the pre-aneurysmal ICA. In Group B and C we evaluated the distribution of biomarkers at paraclinoid ICA which are known to be sites prone to initiation of ICA aneurysms.

Quantitative Evaluation

We hypothesized that aneurysms occur locally from the sites where vascular biomarkers are highest. Our qualitative analyses showed WSS and SWSSG were the only viable biomarkers (Table 3). Based on this, we performed quantitative analyses for WSS and SWSSG. We calculated the highest WSS and SWSSG values at the locations where WSS and SWSSG were qualitatively higher at paraclinoid ICA. The highest WSS was divided by the mean WSS at ICA C2 segment, i.e., inlet portion, and this was defined as the normalized highest-WSS (nh-WSS). The highest SWSSG was divided by the mean WSS at ICA C2 segment, and multiplied by the mean travel distance per 1 time-step during CFD analysis, and this was defined as the normalized highest-SWSSG (nh-SWSSG). Using statistical analysis software (SPSS v23; IBM, Illinois, USA), the Mann-Whitney U test was performed between Group A and Group C, and between Group B and Group C, while the Wilcoxon signed rank test was performed between Group A and Group B. A p-value less than 0.05 was considered statistically significant. The Bonferroni multiple-comparison correction was performed, and the p value was adjusted. In addition, we performed receiver operating characteristic (ROC) analysis in order to quantitatively differentiate the group where aneurysms would occur in the future from the group

where initiation would not occur, and calculated the area under the ROC curve and the Youden index value. The nh-WSS and nh-SWSSG at maximum Youden index value [20] were used as threshold values, and the sensitivity, specificity, and accuracy were verified.

RESULTS

Qualitative Evaluation

High WSS and high SWSSG at and near the aneurysm initiation site was observed in 13 of 15 cases in Group A (Fig 2, Table 3). These distributions were often seen in the boundaries of superior and lateral segment or in medial segment of paraclinoid ICA. Although GON displayed a high distribution at and near the sites of future aneurysm initiation in 7 out of 15 cases, it was a noisy distribution compared to the other biomarkers, and did not show a high distribution at the same sites where the WSS and SWSSG were high (Fig 2). Distributions showing high OSI at the same site and low AFI at the same site were both 1 out of 15 cases (Fig 2, Table 1). The streamlines had high flow velocities at and near the sites of future aneurysm initiation in 11 out of 15 cases (Fig 2).

In Group B, the WSS and SWSSG were high at similar sites as the sites of aneurysm initiation in Group A compared to the surroundings (Fig 3). In addition, there were few showing distributions where OSI was high compared to the surroundings, and distributions where AFI was low compared to the surroundings (Fig 3).

In all Group C cases, high WSS and SWSSG were seen at the boundaries of superior and lateral segment or in medial segment of paraclinoid ICA, similar sites as those of aneurysm initiation in Group A (Fig 4). High OSI at similar sites were

shown in 8 of 33 cases, and low AFI at similar sites was shown in 5 out of 33 cases (Fig 4). In qualitative evaluation, the WSS and SWSSG distributions were very similar between the group where aneurysms occurred and the group where they did not.

Quantitative Evaluation

nh-WSS and nh-SWSSG were both significantly higher in Group A than in Group C (nh-WSS, p=0.045; nh-SWSSG, p=0.0001) (Fig 5). No significant difference was seen between Group B and Group C (nh-WSS, p=0.162; nh-SWSSG, p=0.126) (Fig 5). No significant difference in nh-WSS was seen between Group A and Group B (Fig 5A), however a significant difference was seen in nh-SWSSG (nh-WSS, p=1.00; nh-SWSSG, p=0.016) (Fig 5B).

As a result of ROC analysis between Group A and Group C, the area under the ROC curve for nh-WSS was 0.77, the Youden index maximum value was 0.47, and the nh-WSS value at this time was 6.34 (Fig 6). When this was used as a threshold value, the sensitivity was 0.92, specificity 0.47, and accuracy 1.38. The area under the ROC curve for nh-SWSSG was 0.83, the Youden index maximum value was 0.67, and the nh-SWSSG value at this time was 22.96. When this was used as a threshold value, the sensitivity was 0.83, specificity 0.80, and accuracy 1.63 (Fig 6).

DISCUSSION

A tendency was seen for WSS and SWSSG to be higher at and near the sites of the initiation of the paraclinoid ICA aneurysms compared to the surroundings (Fig 2), corresponding previous studies [2, 3, 13-15, 16, 21]. Matrix metalloproteinase is

produced in vascular walls with high WSS and SWSSG, and is known to trigger wall apoptosis [21-23]. It is thought that the resulting thinning of the walls triggers local protrusion. However, because the same tendency was seen even in groups without aneurysms in the internal carotid artery in this study (Fig 3, 4), we thought that there might be a threshold value in WSS and SWSSG that led to the initiation of aneurysms.

We hypothesized that aneurysms occurred locally from the sites with highest WSS and/or SWSSG, and focused on the WSS and SWSSG as the regions of highest interest. nh-WSS and nh-SWSSG was higher in the patient group with ICA aneurysms (group A) than in the patient group without these (group C), and a statistically significant difference was seen (Fig 5). No significant difference in WSS values was seen between Group A and contralateral healthy ICAs of the aneurysms (Group B) (Fig 5A), but a significant difference was seen in nh-SWSSG (Fig 5B). From this, it was thought that SWSSG was more involved in the initiation of aneurysms than WSS.

Hemodynamics constantly remodels the vascular wall and can help to keep it in good condition [13, 24] or lead to mural cell apoptosis and vascular remodeling on the outward protrusion (aneurysm). According to the Youden index of the ROC analysis, by assuming an nh-WSS of 6.340 and nh-SWSSG of 0.83 to be a threshold value, it was thought possible to differentiate the group where aneurysms would occur in the future and the group where they would not.

There were some limitations of our study. In the CFD analysis, the vascular walls were hypothesized to be rigid no-slip walls, and blood to be an incompressible Newtonian fluid. Our CFD results based on the assumption that blood is Newtonian fluid and the vascular wall is not pulsatile but rigid might not reflect the true

biological phenomenon in vivo. The aneurysm deletion methods for reproducing the pre-aneurysmal geometry were not software-based automated methods of H. Chen et al. [14] but were deleted manually and may not have been accurate. Assuming that hemodynamics did not change before and after aneurysm initiation, we used post-aneurysmal data of the inlet and outlet boundary conditions for the CFD analysis of pre-aneurysmal ICA. Our current retrospective study was limited by the relatively small number of subjects in only two related facilities.

The cases in this study without aneurysms in the ICA had aneurysms at other locations. It would be a topic for future study to investigate whether there are significant differences of nh-WSS and nh-SWSSG between cases with and without aneurysms at other sites.

CONCLUSIONS

We performed the CFD analysis based on the MR data for pre-aneurysmal ICAs and for ICAs without aneurysm, and evaluated the various vascular wall biomarkers. High WSS and SWSSG locations were observed at and near the site of ICA aneurysm initiation of the pre-aneurysmal ICA, and the groups where future aneurysms occurred had significantly higher nh-WSS and nh-SWSSG compared to the groups where it did not. It might be possible to predict the likelihood of aneurysm initiation in the paraclinoid ICA with this technique.

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FIGURE LEGENDs

Fig.1 Flow chart showing the study population and patient selection

ICA, internal carotid artery

Fig.2 Anterior to posterior views of pre- and post-aneurysmal vascular geometry of a representative case of the affected-side ICA group with aneurysm in the paraclinoid ICA (Group A) and anterior to posterior views of vascular biomarkers at and near the aneurysm initiation site in the pre-aneurysmal ICA

Vascular geometry of aneurysm in the superior segment of paraclinoid ICA (A), vascular geometry after removal of aneurysm (B), contour images of systolic WSS (C), systolic SWSSG (D), OSI (E), GON (F), AFI (G) and systolic streamline (H) are shown. The yellow arrow indicates the aneurysm prior to aneurysm removal (A). The yellow arrowhead indicates the site after aneurysm removal (B). The small arrows show where the WSS (C), SWSSG (D), and GON (E) and flow velocity distribution (H) is high compared to the surroundings.

Group A, future aneurysm initiation group; AFI, aneurysm formation index; GON, gradient oscillatory number; ICA, internal carotid artery; OSI, oscillatory shear index; SWSSG, spatial WSS gradient; WSS, wall shear stress

Fig.3 Anterior to posterior views of vascular geometry of a representative case of the contralateral healthy-side paraclinoid ICA on the opposite side group with aneurysm (Group B) and anterior to posterior views of the vascular biomarkers of paraclinoid ICAs

Vascular geometry used in analysis (A), contour images of systolic WSS (B), systolic SWSSG (C), OSI (D), GON (E), AFI (F) and systolic streamlines(G) are shown. Yellow arrows show where the WSS (B), SWSSG (C) and flow velocity distribution (G) is high compared to the surroundings.

Group B, opposite side group of future aneurysm initiation group; AFI, aneurysm formation index; GON, gradient oscillatory number; ICA, internal carotid artery; OSI, oscillatory shear index; SWSSG, spatial WSS gradient; WSS, wall shear stress

Fig.4 Left to right views of vascular geometry of a representative case of the group with no aneurysm in the paraclinoid ICA (Group C) and left to right views of the vascular biomarkers of paraclinoid ICAs

Vascular geometry used in analysis (A), contour images of systolic WSS (B), systolic SWSSG (C), OSI (D), GON (E), AFI (F) and systolic streamlines (G) are shown. Yellow arrows show where the WSS (B), SWSSG (C) and GON distribution (E) is high compared to the surroundings.

Group C, no aneurysm initiation group; AFI, aneurysm formation index; GON, gradient oscillatory number; ICA, internal carotid artery; OSI, oscillatory shear index; SWSSG, spatial WSS gradient; WSS, wall shear stress

Fig.5 Boxplots comparing distribution of nh-WSS and nh-SWSSG in each group

Boxplot of nh-WSS (A) and Boxplot of nh-SWSSG (B) for Group A (future aneurysm initiation group), Group B (opposite side group of future aneurysm initiation group) and Group C (no aneurysm initiation group) are shown.

SWSSG, spatial WSS gradient; WSS, wall shear stress

Fig.6 ROC curve for nh-WSS and nh-SWSSG between the affected-side paraclinoid ICA group with future aneurysm initiation (Group A) and the aneurysm-free paraclinoid ICA group (Group C)

The ROC curve for nh-WSS shows that the maximum Youden index value is 0.383 (green arrow) and the nh-WSS at this point is 6.340. The ROC curve for nh-SWSSG shows that the maximum Youden index value is 0.633 (blue arrow) and the nh-SWSSG at this point is 22.956.

Group A, future aneurysm initiation group; Group C, no aneurysm initiation group; ICA, internal carotid artery; nh, normalized highest; ROC, receiver operating characteristic; SWSSG, spatial WSS gradient; WSS, wall shear stress;

Table 1: Patient demographics

Item	Group A and B	Group C
Number of patients	15	20
Sex (M:F)	3:12	10:10
Age (year)	26-79 (average, 54.8)	42-81 (average, 66.6)
Number of aneurysms	15	25
Aneurysm size (mm)	3.2-5.8 (average, 4.6)	1.6-8.6 (average, 3.9)

Group A, future aneurysm initiation group; Group B, opposite side group of future aneurysm initiation group; Group C, no aneurysm initiation group

Table 2: Aneurysm locations in Group C

Aneurysmal location	Number of patients
Unilateral MCA aneurysm	10
Bilateral MCA aneurysms	2
A-com aneurysm	3
Basilar tip aneurysm	2
BASCA aneurysm	1
MAC, SCA, ACA aneurysms	1
BA tip and bilateral MCA aneurysms	1

Group C, no aneurysm initiation group; ACA, anterior cerebral artery; A-com, anterior communicating; BA, basilar artery; BASCA, basilar artery-superior cerebellar artery bifurcation aneurysm; MCA, middle cerebral artery; SCA, superior cerebellar artery

Table 3: Results of qualitative visual evaluation of vascular biomarkers of the aneurysm initiation site at the pre-aneurysmal paraclinoid ICA in the patients with ICA aneurysm (Group A)

Vascular biomarkers	Number of cases/Total
high WSS at peak systole	13/15
high SWSSG at peak systole	13/15
high OSI	1/15
high GON	7/15
low AFI	1/15
high velocity streamlines at peak systole	11/15

Group A, future aneurysm initiation group; AFI, aneurysm formation index; GON, gradient oscillatory number; ICA, internal carotid artery; OSI, oscillatory shear index; SWSSG, spatial WSS gradient; WSS, wall shear stress