Pencil Beam Presaturation Magnetic Resonance Imaging Helps to Identify Patients at Risk for Intolerance to Temporary Internal Carotid Artery Occlusion During Carotid Endarterectomy…

Tanaka, Jun ; Hosoda, Kohkichi ; Matsuo, Kazuya ; Kyotani, Katsusuke ; Takemoto, Youta ; Yamamoto, Yusuke ; Fujita, Atsushi ; Kohta, Masaaki …

(Citation)
World Neurosurgery,130:e899-e907

(Issue Date)
2019-10

(Resource Type)
journal article

(Version)
Accepted Manuscript

*Title Page

Title:

BeamSAT MRI helps to identify patients at risk for intolerance to temporary internal carotid artery occlusion during CEA and CAS

Authors:

Jun Tanaka,[1] MD, Kohkichi Hosoda,[2] MD, PhD, Kazuya Matsuo,[1] MD, Katsusuke Kyotani,[3] MSc, Youta Takemoto,[3] AD, Yusuke Yamamoto,[1] MD, PhD, Atsushi Fujita,[1] MD, PhD, Masaaki Kohta,[1] MD, PhD, Hidehito Kimura,[1] MD, PhD, Takashi Sasayama,[1] MD, PhD, Eiji Kohmura,[1] MD, PhD

Affiliations:

Department of Neurosurgery,[1] Kobe University Graduate School of Medicine, 7-5-1, Kusunoki-cho, Chuo-ku, Kobe 650-0017, Japan

Department of Neurosurgery,[2] Kobe City Nishi-Kobe Medical Center, 5-7-1, Kojidai, Nishi-ku, Kobe, 651-2273, Japan

Center for Radiology and Radiation Oncology,[3] Kobe University Hospital, 7-5-1, Kusunoki-cho, Chuo-ku, Kobe 650-0017, Japan

Corresponding Author's name and current institution:

Kohkichi Hosoda, MD, PhD

Department of Neurosurgery, Kobe City Nishi-Kobe Medical Center, 5-7-1, Kojidai, Nishi-ku, Kobe, 651-2273, Japan

Corresponding Author's Email:

khosoda@med.kobe-u.ac.jp

Funding:

Hosoda K. is supported in part by a Grant-in-Aid for Scientific Research (C) KAKENHI Number 15K10302 and 18K08994 from the Japan Society for the Promotion of Science.

Acknowledgments:

Mr. Nishihara (Hitachi, Ltd. Healthcare Business Unit) is gratefully acknowledged for providing technical assistance with the image data analysis and for his helpful discussions.

Abstract

Objective

There has been no effective method to predict ischemic intolerance to temporary internal carotid artery (ICA) occlusion during carotid artery reconstruction. Pencil beam pre-saturation (BeamSAT) pulse suppresses the flow signal of target vessel in magnetic resonance angiography (MRA). Applying this method, we construct “ICA-selective MRA” images. The aim of the current study is to identify patients at risk for ischemic intolerance by ICA-selective MRA.

Methods

By evaluating flow of Acom, A1 portion of anterior cerebral artery with ICA-selective MRA, and Pcom with conventional MRA, we investigated associations of these collateral flow patterns with ischemic intolerance and the decrease of regional cerebral oxygen saturation (rSO2).

Results

Fifty-eight patients who underwent CEA/CAS were included. Six of 7 patients without Acom flow and Pcom flow demonstrated ischemic intolerance, while all patients ($n = 51$) with Acom and/or Pcom flow demonstrated tolerance. The accuracy of this prediction model according to Acom and Pcom flow patterns for ischemic intolerance was 0.98 ($p = 0.01$, binomial test). The decrease of rSO2 after ICA occlusion was significantly larger in patients without Acom flow and Pcom flow (12.0±6.0%) than in those with Acom flow and Pcom flow (3.0±3.1%, $p < 0.01$) and in those with Acom flow but no Pcom flow (2.4±5.2%, $p < 0.01$).

Conclusions

These findings support the importance of Acom flow as a collateral route. ICA-selective MRA enables an excellent prediction of ischemic intolerance to temporary ICA occlusion during CEA or CAS. This method provides valuable information regarding the probability of an ischemic complication.

Keywords:

BeamSAT, ICA-selective MRA, intolerance, CEA, CAS

Abbreviations and Acronyms:

ACA: Anterior Cerebral Artery

Acom: Anterior Communicating Artery

ASL: Arterial Spin Label

BeamSAT: Pencil Beam Pre-saturation

CAS: Carotid Artery Stenting

CBF: Cerebral Blood Flow

CEA: Carotid Endarterectomy

CoW: Circle of Willis

CTA: Computed Tomography Angiography

ICA: Internal Carotid Artery

MRI: Magnetic Resonance Imaging

MRA: Magnetic Resonance Angiography

NIRS: Near Infrared Spectroscopy

rSO_2: Regional Cerebral Oxygen Saturation

SEP: Somatosensory-evoked Potential

TOF: Time of Flight

Introduction:

Carotid endarterectomy (CEA) and carotid artery stenting (CAS) have been established to be effective treatment methods for preventing cerebral infarction in patients with carotid artery stenosis. [1-4] In all CEA cases and CAS cases using the balloon protection device, intraoperative temporary internal carotid artery (ICA) occlusion is inevitable. However, some patients demonstrate ischemic intolerance to temporary ICA occlusion. Among patients with carotid stenosis, the incidence of ischemic intolerance to intraoperative temporary ICA occlusion is reported to be 8.7-21%.[5-11] In intolerant cases of CEA, insertion of an intraluminal shunt is required, however which may be related to intraoperative complications, such as stroke caused by a dislodged embolic plaque. [6] In CAS using the balloon protection device, unanticipated intraoperative brain ischemia may cause decreased level of consciousness and focal hemispheric deficit. [12] Accordingly, it is important to predict ischemic intolerance to temporary ICA occlusion preoperatively: whether a shunt should be used in CEA cases or a filter protection device should be used in CAS cases. However, the preoperative prediction method of ischemic intolerance has not been established.

Pencil beam pre-saturation (BeamSAT) pulse, a new imaging method of magnetic resonance imaging (MRI), enables suppression of the flow signal of a target vessel in 3D time of flight (TOF) magnetic resonance angiography (MRA). [13] Applying this method, we are able to construct “ICA-selective MRA” images. Catheter-based angiogram is commonly used to evaluate the cortical arterial perfusion area from the unilateral ICA. However, the catheter-based angiogram may not reflect the exact cortical hemodynamics due to mechanical-driven power injection of contrast medium. Different from the catheter-based angiogram, ICA-selective MRA is not only less invasive without arterial catheterization and radiation exposure but is also more suitable for evaluating the physiological flow pattern because it requires no mechanical-driven power injection of contrast medium. This ICA-selective MRA enables us to demonstrate the natural flow of the anterior communicating artery (Acom) in patients with carotid stenosis, which is important as a collateral route during ICA temporary occlusion. [14 15] In addition, the bilateral A1 portions of the anterior cerebral artery (ACA), which form the anterior segment of the circle of Willis (CoW) with the Acom and posterior communicating artery (Pcom), could also work as collateral routes. Accordingly, we hypothesize that the flow pattern of these collateral routes determines the ischemic intolerance of patients during ICA occlusion. The aim of the current study is to validate this hypothesis and to identify patients at risk for ischemic intolerance to temporary ICA occlusion during CEA and CAS using ICA-selective MRA constructed by application of BeamSAT MRA.

Methods:

Patients

We performed a prospective cohort study using MRI in patients with carotid stenosis to assess the clinical usefulness of arterial spin label (ASL) in cerebral blood flow (CBF) assessments and to investigate the association between magnetic resonance plaque imaging findings and the risk of new ischemic lesions after either CEA or CAS. [16-18] Accordingly, we prospectively recruited patients who were under consideration for either CEA or CAS and retrospectively reviewed the BeamSAT results of these patients in the current study. Between March 2015 and November 2018, 58 consecutive patients underwent carotid revascularization procedures (39 CEAs and 19 CASs) for carotid stenosis. Fifty of these patients met inclusion criteria and were included in the current study. The inclusion criteria were carotid stenosis of ≥50% for symptomatic cases and stenosis of ≥60% for asymptomatic cases according to the criteria of previous studies. [1 2] Symptomatic patients were defined as those who had experienced amaurosis fugax, a transient ischemic attack, or a stroke in the territory of the ipsilateral carotid artery within 6 months before entry. We performed MRI with BeamSAT pulse and constructed ICA-selective MRA before carotid revascularization. Our institutional review board approved this study, and written informed consent was obtained from all patients.

Surgical Procedures

Our surgical procedures for CEA and CAS have been previously reported.[19] CEA was performed under general anesthesia and somatosensory-evoked potential (SEP) monitoring for selective placement of the shunt. CAS were performed under local anesthesia and general heparinization. In both procedures, regional cerebral oxygen saturation (rSO_2) was monitored by near infrared spectroscopy (NIRS).

Definition of Intolerance

In the CEA cases, ischemic intolerance was defined as a ≥50% reduction of the SEP amplitude after ICA occlusion compared with the pre-occlusion level. In the CAS cases, ischemic intolerance was defined as the emergence of ischemic neurological deficits, such as disturbed consciousness, hemiparesis, aphasia, or agitation.

BeamSAT Pulse

MRI studies were performed using a 1.5-T MRI scanner (ECHELON Vega; Hitachi, Tokyo, Japan) and an 8-channel head coil. A 3D TOF MRA was obtained with the following scan parameters: TR/TE = 23.0/6.9 ms, FA = 20 deg, FOV = 230 mm, matrix = 512 × 200, slice interval = 0.55 mm (after zero-fill interpolation), number of slices = 152, and acquisition time = 4:50. For the selective 3D TOF MRA, the positioning of the BeamSAT pulse was performed on a TOF source image of a conventional MRA (Fig. 1A), and suppression of the flow signal in the target arterial region on the 3D TOF MRA was achieved (Fig. 1B and C). [13] The BeamSAT pulse was set prior to the TOF sequence in each TR, and the TR was extended from 23.0 ms to 40.5 ms. To suppress only the target artery, a BeamSAT pulse with a 30 mm diameter was positioned to cover the target artery.

“ICA-selective MRA” Image

“ICA-selective MRA” was obtained as follows: by adjusting the insertion direction of the BeamSAT pulse to penetrate and suppress the flow signals of the three major vessels (e.g., right ICA and bilateral vertebral arteries) (Fig. 1D and E), only the target ICA (e.g., left ICA) flow signal was left over and an “ICA-selective MRA” was obtained (Fig. 1F).

Classification of the Arterial Flow of the Anterior Segment of the CoW and Acom Flow Evaluation

By using ICA-selective MRA, we classified the arterial flow patterns of the anterior segment of the CoW into 3 groups: (1) when the bilateral ACAs corresponding A2 and distal to A2 were perfused from the ICA of the contralateral side via the Acom and the ICA of the stenotic side perfused only the ACA on the stenotic side, they were classified into the Acom (+)/A1 (+) group (Fig. 2A). This flow pattern indicates the presence of Acom flow and A1 flow; (2) when the bilateral ACAs (distal to A2) were perfused only from the ICA of the unilateral side and the contralateral A1 was not visualized, they were classified into the Acom (+)/A1 (–) group (Fig. 2B). This flow pattern indicated congenital A1 hypoplasia either on the stenotic or non-stenotic side; and (3) when the ACAs corresponding A2 and distal to A2 on each side were perfused only from the ipsilateral A1 (the right ACA was visualized only in the right ICA-selective MRA, and the left ACA was visualized only in the left ICA-selective MRA), they were classified into the Acom (–)/A1 (+) group (Fig. 2C). This flow pattern indicated no effective Acom flow. These flow patterns were judged cautiously based on TOF source images as well as 3D TOF images by ICA-selective MRA by two observers (J.T and K.M, both were Japan Neurosurgical Society board certificated neurosurgeon). In addition, we also evaluated the arterial flow patterns of the anterior segment of the CoW by conventional 1.5T-MRA to see the difference between ICA-selective MRA and conventional MRA.

Posterior Communicating Artery (Pcom) Flow Evaluation

The presence of Pcom flow was assessed by conventional MRA. Patients whose Pcom flow was recognized were classified into the Pcom (+) group (Fig. 3A). Patients without Pcom flow were classified into the Pcom (–) group (Fig. 3B).

Regional Cerebral Oxygen Saturation (rSO_2) Monitoring

We monitored rSO2 as a quantitative barometer of cerebral ischemia by using a NIRS oximeter (INVOSTM 5100C Cerebral Oximeter, Medtronic, Minneapolis, MN, USA). [20] Adhesive optode pad sensors were placed at the bilateral frontotemporal area. Monitoring of rSO2 was started before anesthetic induction, and we checked the rSO2 value continuously every one minute during the operation. We measured the difference in the rSO2 value before and after ICA clamp during ECA occlusion for CEA and the difference before and after distal ICA balloon inflation for CAS.

Statistical Analysis:

Statistical analyses were performed with open-source software (R3.4.0). Descriptive statistics are presented as the mean ± SD and were compared using Welch t test. The proportions were compared with Fisher exact test. The significance of differences among more than 2 groups was determined with Tukey-Kramer test. The ischemic intolerance prediction model was assessed in terms of its prediction accuracy. Overall accuracy rate was computed using binomial test and one-sided test to determine whether the accuracy is better than the "no information rate," which is taken as the largest class percentage. Probability values of <0.05 were considered statistically significant. Agreement between observers in the CoW categorization was calculated using Cohen's kappa test. [21] The obtained values were interpreted according to the criteria of Landis and Koch: values greater than 0.81 represent excellent agreement. [22]

Illustrative Intolerant Case

An 84-year-old male underwent CEA for left asymptomatic severe and progressive carotid stenosis. In the pre-operative conventional MRA, there was no ipsilateral Pcom flow, however we could not confirm the existence of Acom flow (Fig. 4A and B). Thus, we referred to the ICA-selective MRA; in the right (non-stenotic side) ICA-selective MRA, the right ACA was perfused only from the right ICA (Fig. 4C). On the other hand, in the left (stenotic side) ICA-selective MRA, the left ACA was perfused only from the left ICA (Fig. 4D). The source images of bilateral ICA-selective MRA also guaranteed no Acom flow. Hence, these findings indicated no Acom flow (group Acom (–)/A1 (+)). While the patient underwent CEA, rSO_2 was drastically decreased (before: 67%, after: 49%) and the SEP amplitude dropped to <50% immediately after the left ICA occlusion. We judged that he was intolerant to ICA temporary occlusion and inserted a shunt.

After inserting the shunt, rSO_2 and the SEP amplitude rapidly recovered to the pre-occlusion level and the endarterectomy proceeded with no trouble. His postoperative course was uneventful.

Results:

Patients

Of the 58 patients, 50 patients were men and 8 were women. The overall average of the degree of ICA stenosis was 61.2±24.8% according to the NASCET criteria. Six patients were intolerant to temporary ICA occlusion (CEA: 5, CAS: 1). The other characteristics are shown in Table 1. There was no statistically significant difference between tolerant and intolerant patients in the baseline characteristics. No patients experienced an ischemic complication related to temporary ICA occlusion.

Flow Pattern of the Anterior Segment of the CoW

The Cohen's kappa test between observers (J.T and K.M) for the CoW categorization by ICA-selective MRA showed an extremely high kappa value (kappa = 0.95, 95% confidence interval [CI], 0.90-1.01; $p < 0.01$) by demonstrating an optimal inter-observer concordance. Agreement is considered almost perfect for 0.81-1.0 of kappa.

By ICA-selective MRA, we were able to exactly classify all patients into 3 groups; 33 patients belonged to the Acom (+)/A1 (+) group (Table 2). In most patients (n = 32; 97.0%), the Acom flow seemed to be directed from the non-affected side to the affected side. Ten patients belonged to the Acom (+)/A1 (–) group. A1 hypoplasia was recognized in 4 patients on the stenotic side and in 6 patients on the contralateral side. Fifteen patients belonged to the Acom (–)/A1 (+) group.

On the contrary, by conventional MRA, only 24 patients were clearly classified into a certain flow pattern (Acom (+)/A1 (+) group: 14 patients, Acom (+)/A1 (–) group: 10 patients), and the remaining 34 patients were not able to be classified into an appropriate flow pattern because the delineation of Acom flow was unclear. In contrast to the 24 patients whose Acom or A1 flow were delineated clearly, the remaining 34 patients demonstrated closely contiguous bilateral A1-A2 junctions, even with referring to TOF source images of MRA, and consequently, their Acom flow could not be fully confirmed. In another observer's (K.M) evaluation by conventional MRA, 32 patients were classified into a certain flow pattern (Acom (+)/A1 (+) group: 22 patients, Acom (+)/A1 (–) group: 10 patients) and 26 patients could not be confirmed the existence of Acom flow. In contrast to the ICA-selective MRA, the Cohen's kappa test between observers (J.T and K.M) for the CoW categorization by conventional MRA showed a moderate kappa value (kappa = 0.53, 95% confidence interval [CI], 0.31-0.74; $p < 0.01$).

Pcom Flow Evaluation

We were able to evaluated Pcom flow of all patients. Thirty-six patients belonged to the Pcom (+) group (Table 2). This group included 8 patients with a fetal type of Pcom. Twenty-two patients belonged to the Pcom (–) group.

Relationship between the Collateral Flow Patterns and Ischemic Intolerance During Temporary ICA Occlusion

No patients had perioperative infarctions, which influence the ICA perfusion territory. Among the 58 patients, 6 demonstrated ischemic intolerance during temporary ICA occlusion. The prediction of ischemic tolerance according to the individual artery flow pattern, namely A1, Acom or Pcom flow, was not statistically significant (Table 2). The accuracy of the prediction of ischemic intolerance according to the A1 flow, i.e., Acom (+)/A1 (+) + Acom (–)/A1 (+) versus Acom (+)/A1 (–), was 0.72 (95% confidence interval [CI], 0.59-0.83; $p = 1.00$; Table 2). The sensitivity of the prediction model was 0, and the specificity was 0.81. The accuracy of the prediction of ischemic intolerance according to the presence of Acom flow, i.e., Acom (+)/A1 (+) + Acom (+)/A1 (–) versus Acom (–)/A1 (+), was 0.84 (95% confidence interval [CI], 0.73-0.93; $p = 0.93$). The sensitivity of the prediction model was 1.00, and the specificity was 0.83. The accuracy of prediction of ischemic intolerance according to the presence of Pcom flow was 0.71 (95% confidence interval [CI], 0.57-0.82; $p = 1.00$). The sensitivity of the prediction model was 1.00, and the specificity was 0.67. We then constructed a prediction model that included the combination the Acom and

Pcom flows, i.e., Acom (+)/Pcom (+) + Acom (+)/ Pcom (–) +Acom (–)/Pcom (+) versus Acom (–)/Pcom (–) (Table 2). The accuracy of this prediction model for ischemic intolerance was 0.98 (95% confidence interval [CI], 0.91-1.00; p = 0.01). The sensitivity of the prediction model was 1.0, and the specificity was 0.98.

Change in rSO_2 Before and After Temporary ICA Occlusion

The decrease in rSO_2 after ICA occlusion during CEA or CAS was significantly larger in the Acom (–)/ Pcom (–) group (12.0 ± 6.0%, n = 7) than in the Acom (+)/ Pcom (+) group (3.0 ± 3.1%, n = 26, p = 0.0036) or Acom (+)/ Pcom (–) group (2.4 ± 5.2%, n = 16, p =0.014) (Fig. 5). No significant difference was observed between the Acom (–)/ Pcom (–) group and Acom (–)/ Pcom (+) group (6.8 ± 5.3%, n = 8).

Discussion:

Ischemic intolerance during temporary ICA occlusion occurs when collateral flow, which is mainly supplied from the contralateral ICA via the anterior segment of the CoW and from the basilar artery via the Pcom, is insufficient. In particular, the anterior segment of the CoW is the most important collateral route. [14 15] Nevertheless, the importance of Acom flow has not been discussed scientifically except a few reports. [14 15]

Although CEA and CAS are common procedures, preoperative prediction of ischemic intolerance by conventional MRA has been described only in a few reports. In previous studies of CEAs, 56-60% of carotid stenosis patients with neither Acom flow nor Pcom flow evaluated by conventional MRA were intolerant to ICA temporary occlusion. [8 9] Sussman et al described the absence of both Pcoms on preoperative computed tomography angiography (CTA) or 3T-MRA is predictive of early cognitive dysfunction 24 hours after CEA due to intraoperative hypoperfusion (odds ratio: 56.09). However, they did not refer to whether the absence of Acom flow affected early cognitive dysfunction. [23] Shin et al also reported whether the preoperative 1.5T MRA can predict the risk of cerebral ischemia associated with the CEA. However, their results demonstrated only 20.5% of patients without both of Acom and Pcom flow needed shunt insertion during ICA occlusion of CEA while 7.8% of patients with the presence of Acom or Pcom flow needed shunt insertion, in contrast to the current results which demonstrated 98% prediction accuracy. [24] On the other hand, Lee et al. reported that conventional 1.5T-3D TOF MRA could not predict ischemic intolerance. They considered the Acom to be normally patent if the junctions of the A1 and A2 segments were in close contact with each other and both the proximal A1 segments were approximated, but they assumed that only an approximation could not guarantee the presence of the Acom. [7] These results might suggest there were critical limitation to evaluate Acom flow only by conventional MRA. The current results that 26 or 34 of 58 patients could not be confirmed the existence of Acom flow and there was only low interrater reliability between two observers would indicate a drawback of Acom flow assessment by conventional MRA.

The current results clearly demonstrated the superiority of the ICA-selective MRA constructed by BeamSAT pulse for the detection of Acom flow. All patients without Acom flow and Pcom flow demonstrated ischemic intolerance, with a high prediction accuracy, 98%. The current results of the rSO_2 change before and after ICA temporary occlusion also supported the importance of Acom collateral flow.

Despite Acom being such an important collateral route, it has been difficult to evaluate Acom flow by conventional MRA or CTA because the Acom is a very short and narrow artery. The length of the Acom is 0.3-7.0 mm and its diameter is 0.2-3.4 mm. [25] The incidence of a hypoplastic Acom is 6% and the incidence of an absent Acom is 8% among cadaver dissecting subjects. [26] The results of the conventional MRA in the current study were in line with these previous findings. We were not able to clearly evaluate Acom flow for more than half of patients with carotid stenosis with the conventional MRA. In addition, the evaluation by catheter-based angiogram may not reflect the physiological arterial flow of the anterior segment of the CoW because it requires mechanical-driven power injection of a contrast medium. Accordingly, it has been difficult to predict ischemic intolerance to ICA occlusion with the use of Acom flow pattern detected by the conventional MRA or catheter-based angiogram.

The current method of using ICA-selective MRA constructed by BeamSAT pulse not only offers a reduced complication profile to catheter-based angiography but also enables us to accurately evaluate more physiological Acom flow as described above. The assumption is as follows: the intracranial arterial blood pressure of the stenosed ICA would be lower than that in the non-stenosed side ICA. When the anterior segment of the CoW is complete (bilateral A1 and Acom flow exist), arterial blood should flow from the non-stenosed ICA to the stenosed-side ACA distal to A2 via the Acom, according to the arterial blood pressure gradient between the stenosed and non-stenosed ICA. (Fig. 2A). In fact, Acom flow was shown from the non-stenosed side to stenosed side in 32 of 33 patients (97.0%). In other words, a bilateral ACA on the healthy side ICA-selective MRA indicates the existence of cross flow via the Acom, which might be efficient at recruiting collateral flow. By contrast, when each side of the ACA is supplied only from the ipsilateral ICA and not from the contralateral ICA, it indicates that Acom flow does not exist or seems to be too small to recruit sufficient flow for the prevention of ischemia in carotid stenosis. (Fig. 2B)

Different from the Acom, the Pcom is a relatively large vessel (length: 5.0-18.0 mm, diameter: 0.4-4.0 mm). [25] Accordingly, evaluation of Pcom flow is usually not difficult, even by conventional MRA. Although collateral Pcom flow might not be as sufficient as Acom flow, it supplied enough collateral flow to maintain cerebral blood flow and to ischemic intolerance.

There are some cases with no A1 flow on ipsilateral ICA-selective MRA (Acom (+)/A1 (–) cases) due to A1 hypoplasia (Fig. 2C). The frequency of this congenital variation is 1–13%, as derived from angiograms and autopsy. [27-30] To our knowledge, there has been no report on whether the presence of A1 flow contributes to ischemic intolerance during temporary ICA occlusion. The current study demonstrated that the absence of A1 flow was not associated with ischemic intolerance. In all cases with an A1(–) pattern, as the ipsilateral Pcom was observed to be thick, sufficient collateral flow could be recruited via the Pcom. Another possibility was that leptomeningeal collateral routes from the ipsilateral ACA, via the Acom sourced from the contralateral ICA, may be effective.

In the current study, only patients with relatively severe stenosis of the ICA were included. Accordingly, the current method to predict ischemic intolerance may not be applicable to patients without carotid stenosis as a substitute for ICA balloon test occlusion. In addition, the current method cannot be used to confirm the safety of permanent ICA occlusion.

There are some other limitations of the current study. First, the absence of Acom flow evaluated by ICA-selective MRA does not necessarily mean an anatomical defect of the Acom. However, it is likely that the Acom, the flow of which is insufficient to be visualized with ICA-selective MRA, will not recruit enough collateral flow to compensate for the demand of the ischemic cerebral hemisphere. Second, the collateral flow from the external carotid artery (ECA) or via cortical leptomeningeal flow was not assessed by this MRI technique. Third, the small sample size and thus the imprecision of any predictive values coming from the model are a main limitation of the current study.

Conclusions:

In patients with carotid stenosis, ICA-selective MRA constructed by BeamSAT pulse is useful for evaluating the flow pattern of the anterior segment of the CoW, especially Acom flow. Along with an assessment of the ipsilateral Pcom flow with conventional MRA, ICA-selective MRA enables an excellent prediction of intolerance to temporary ICA occlusion during CEA or CAS. The current approach provides valuable information about the probability of hemodynamic ischemic complication due to temporary ICA occlusion and assists clinicians and patients in their decision-making regarding treatment strategies for carotid stenosis.

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Figure Legend:

Fig. 1

Positioning the BeamSAT pulse to cover a unilateral petrous portion of the ICA in an axial TOF source image of conventional MRA is shown (A). By adding the BeamSAT pulse to the unilateral ICA (B), a 3D TOF MRA in which only the ipsilateral ICA flow signal is suppressed can be obtained (C). By positioning the BeamSAT pulse to suppress the flow signals of a unilateral petrous portion of the ICA and bilateral VAs in an axial TOF source image of conventional MRA (D), which is schematically shown as (E) on 3D TOF MRA, the remaining target contralateral "ICA-selective MRA" can be obtained (F).

Fig. 2

A: Acom (+)/ A1 (+) group. The bilateral ACAs corresponding A2 and distal to A2 are perfused from the ICA of the contralateral side via the Acom and the ICA of the stenotic side perfused only the ACA on the stenotic side. **B:** Acom (+)/A1 (–) group. The bilateral ACAs (distal to A2) are perfused only from the ICA of the unilateral side and the contralateral A1 is not visualized. **C:** Acom (–)/A1 (+) group. The ACA corresponding A2 and distal to A2 on each side was perfused only from the ipsilateral A1 (Right ACA was visualized only in the right ICA-selective MRA, and left ACA was visualized only in the left ICA-selective MRA).

Fig. 3

The presence of Pcom flow is evaluated in a caudal view of conventional MRA.

A: Pcom flow (+) case. White arrowheads indicate the right Pcom.

B: Pcom flow (–) case. No Pcom was recognized.

Fig. 4

Illustrative intolerant case (left carotid stenosis).

Caudal view of conventional MRA does not show the left Pcom flow, and the existence of Acom flow is unclear (A, B). Right ICA-selective MRA visualizes only the right ACA (C), and left ICA-selective MRA only visualizes the left ACA independently (D).

Fig. 5

Box-and-whisker plots of the rSO2 decrease before and after ICA occlusion on the stenotic side during CEA or CAS. The reduction of the rSO_2 is significantly larger in the Acom (–)/Pcom (–) group than in the Acom (+)/Pcom (+) group or the Acom (+)/Pcom (–) group. No significant difference was observed between the Acom (–)/Pcom (–) group and the Acom (–)/Pcom (+) group. The horizontal thick lines divide the boxes at the median values. The bottom and top of the boxes indicate the first and third quartiles. The whiskers extend to the most extreme data points, which are no more than 1.5 times the interquartile range from the box. Patients with intolerance to ICA occlusion are indicated by white circles.

Table(s)

Table 1 Baseline characteristics

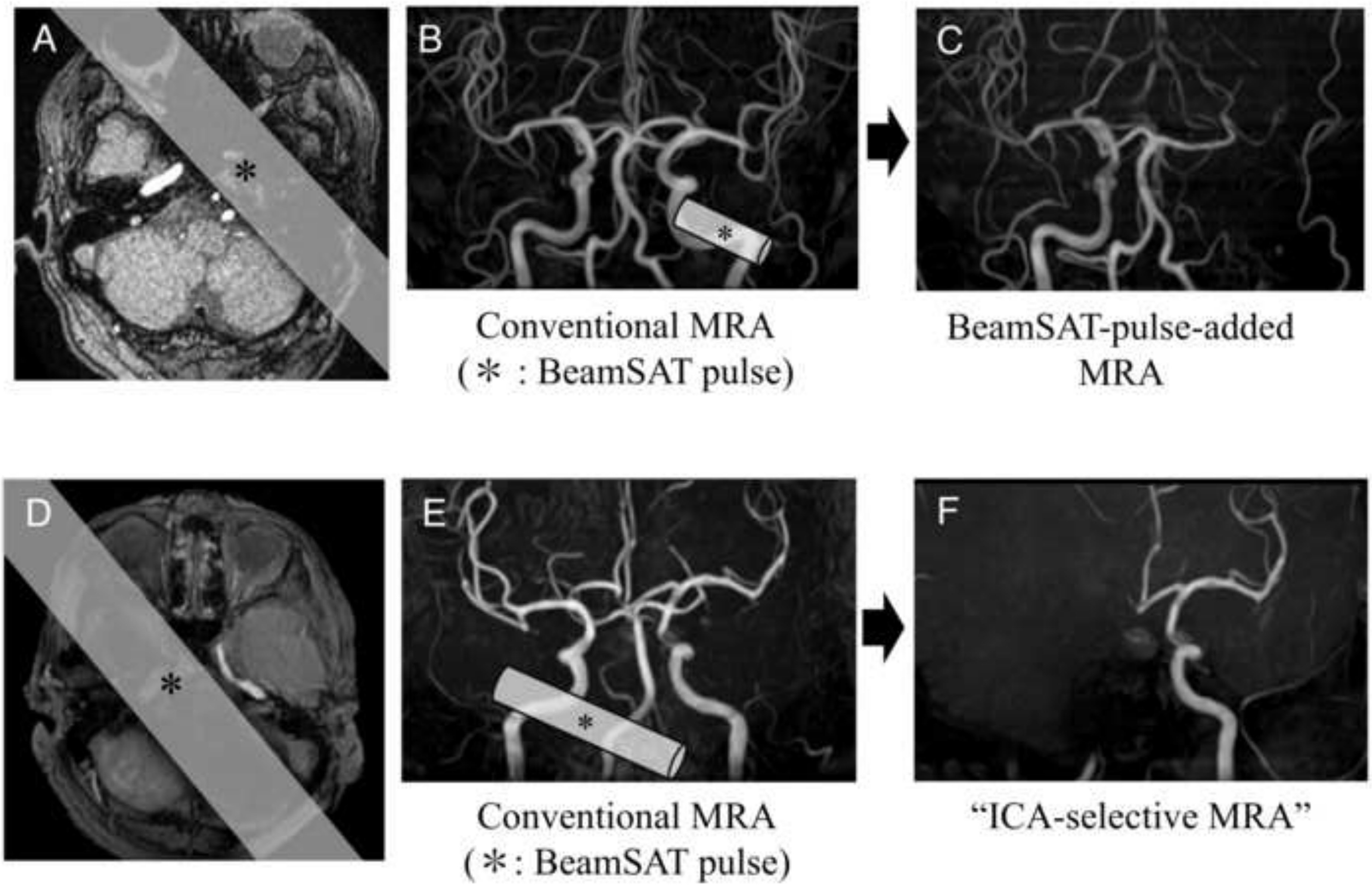
	Tolerant (n = 52)	Intolerant (n = 6)	*P*
CEA	33 (63.4%)	5 (83.3%)	0.65
Age (years)	75.3 ± 7.1	80.0 ± 4.2	0.12
Men	45 (86.5%)	4 (80.0%)	1.00
Degree of stenosis (%)	60.9 ± 24.7	66.2 ± 27.8	0.97
Symptomatic lesions	24 (46.1%)	2 (33.3%)	0.68
Hypertension	37 (71.1%)	5 (83.3%)	1.00
Dyslipidemia	21 (46.2%)	5 (83.3%)	0.19
Diabetes mellitus	20 (38.4%)	3 (50.0%)	0.67
Ischemic heart disease	5 (9.6%)	1 (16.7%)	0.50

Table(s)

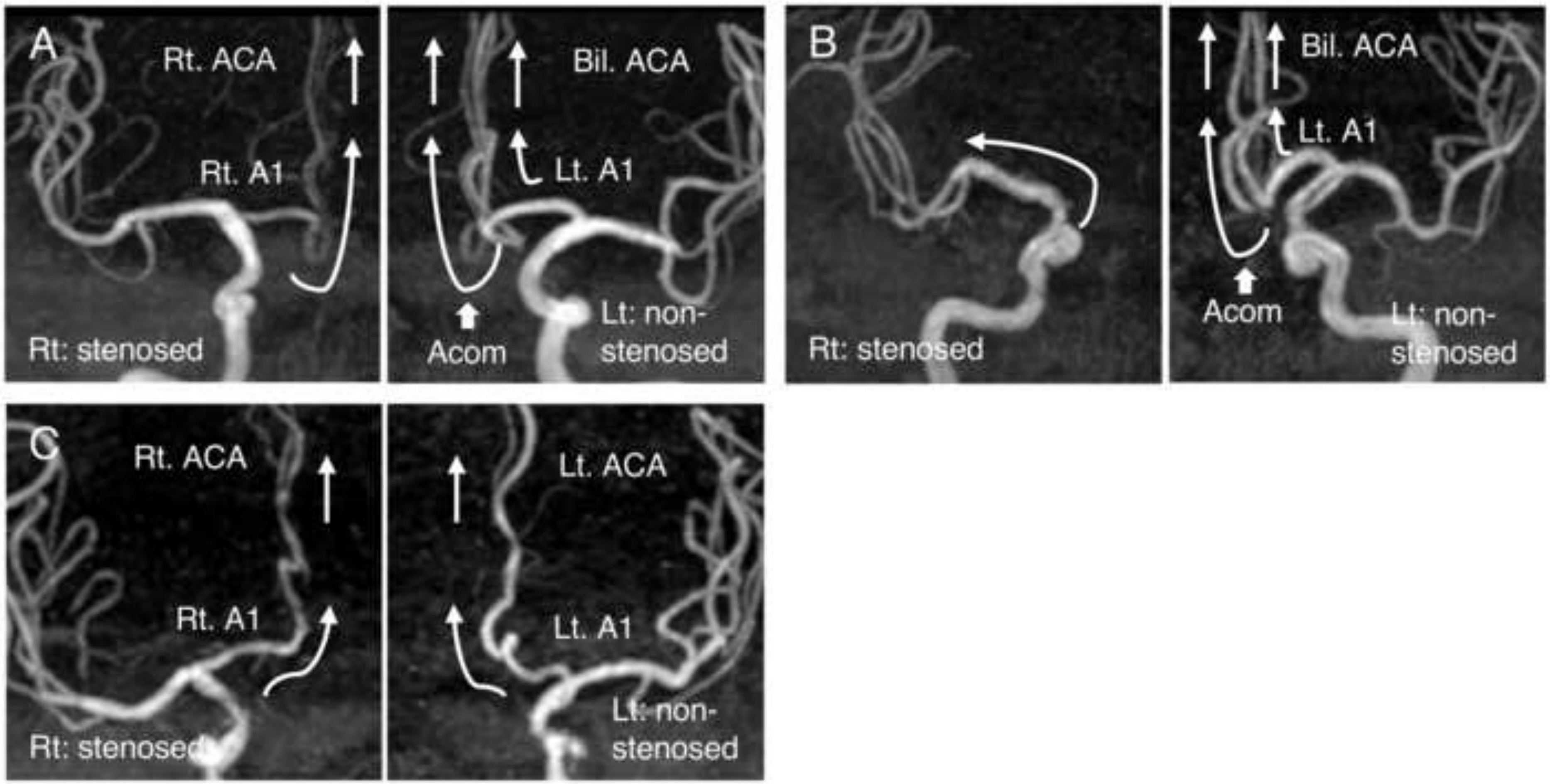
Table 2 Relationship between collateral flow patterns and ischemic tolerance

Flow pattern		Acom (+)		Acom (–)	Total
		A1 (+)	A1 (–)	A1 (+)	
Pcom (+)	Tolerant	19	9	8	36
	Intolerant	0	0	0	0
Pcom (–)	Tolerant	14	1	1	16
	Intolerant	0	0	6	6
Total		33	10	15	58

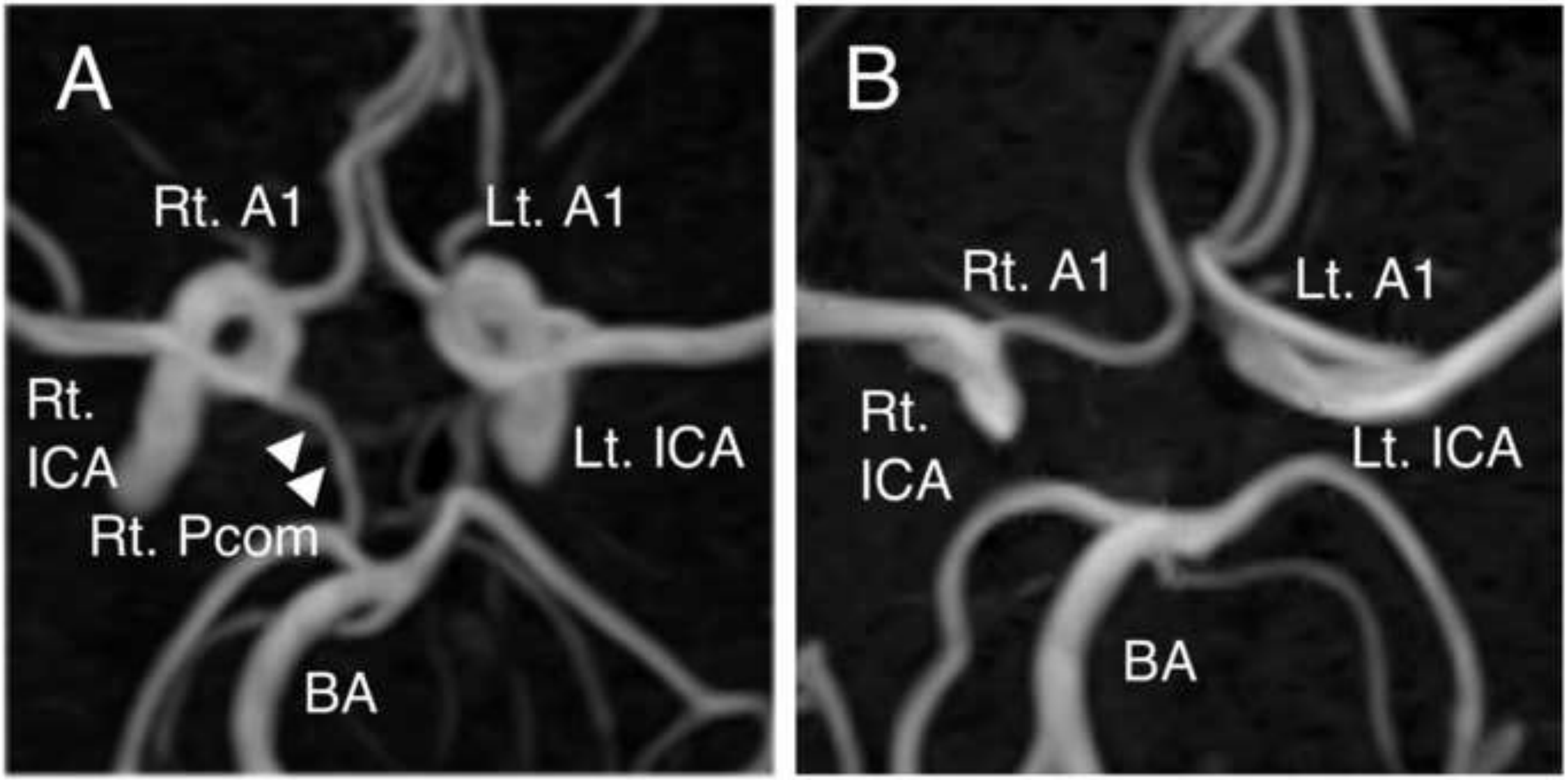
Figure(s)


A
*
B
*
Conventional MRA
(*: BeamSAT pulse)
C
BeamSAT-pulse-added
MRA
D
*
E
*
Conventional MRA
(*: BeamSAT pulse)
F
“ICA-selective MRA”

Figure(s)


A
Rt. ACA
Rt. A1
Rt: stenosed
Bil. ACA
Lt. A1
Acom
Lt: non-stenosed
B
Rt: stenosed
Bil. ACA
Lt. A1
Acom
Lt: non-stenosed
C
Rt. ACA
Rt. A1
Rt: stenosed
Lt. ACA
Lt. A1
Lt: non-stenosed

Figure(s)



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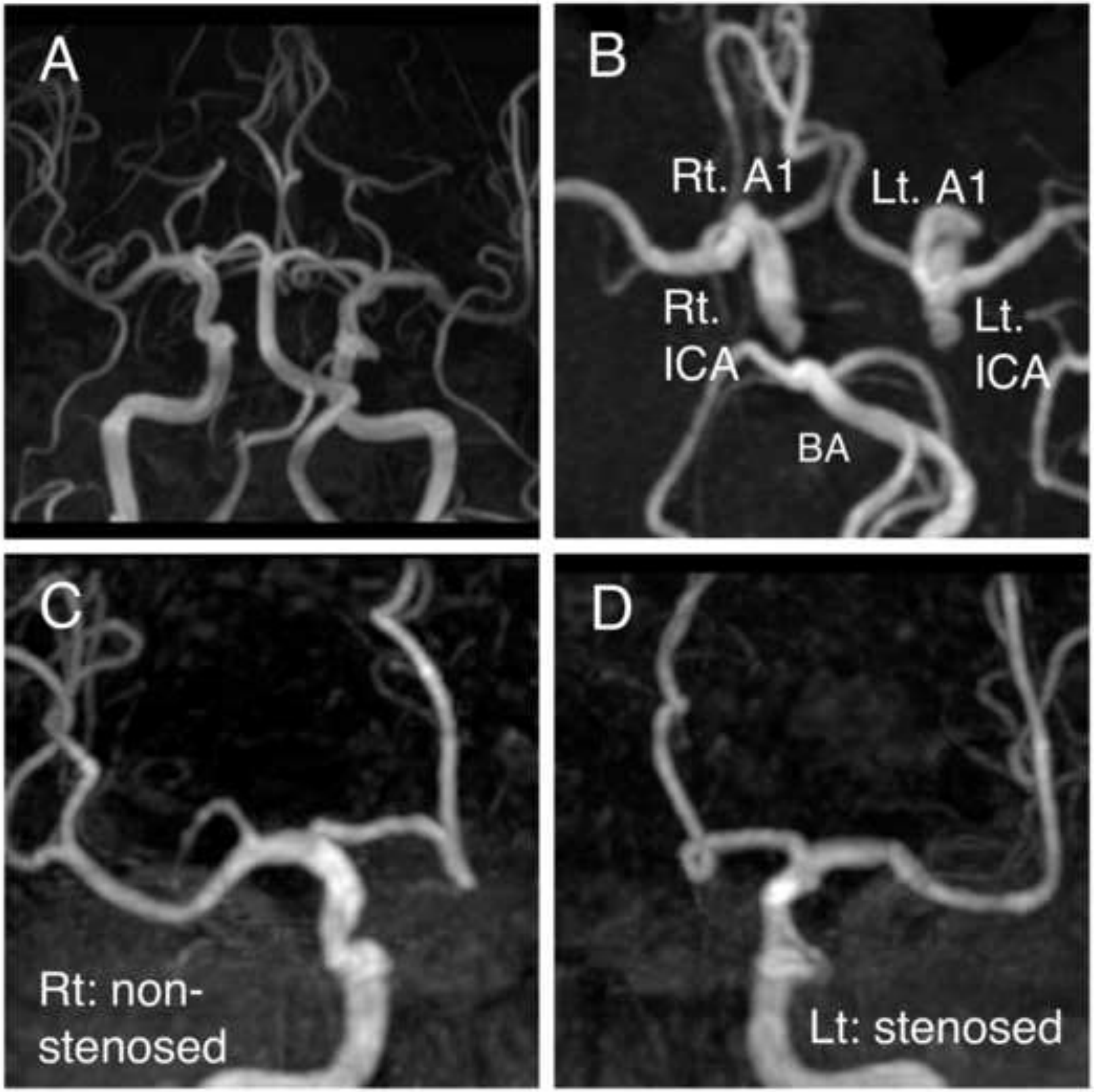

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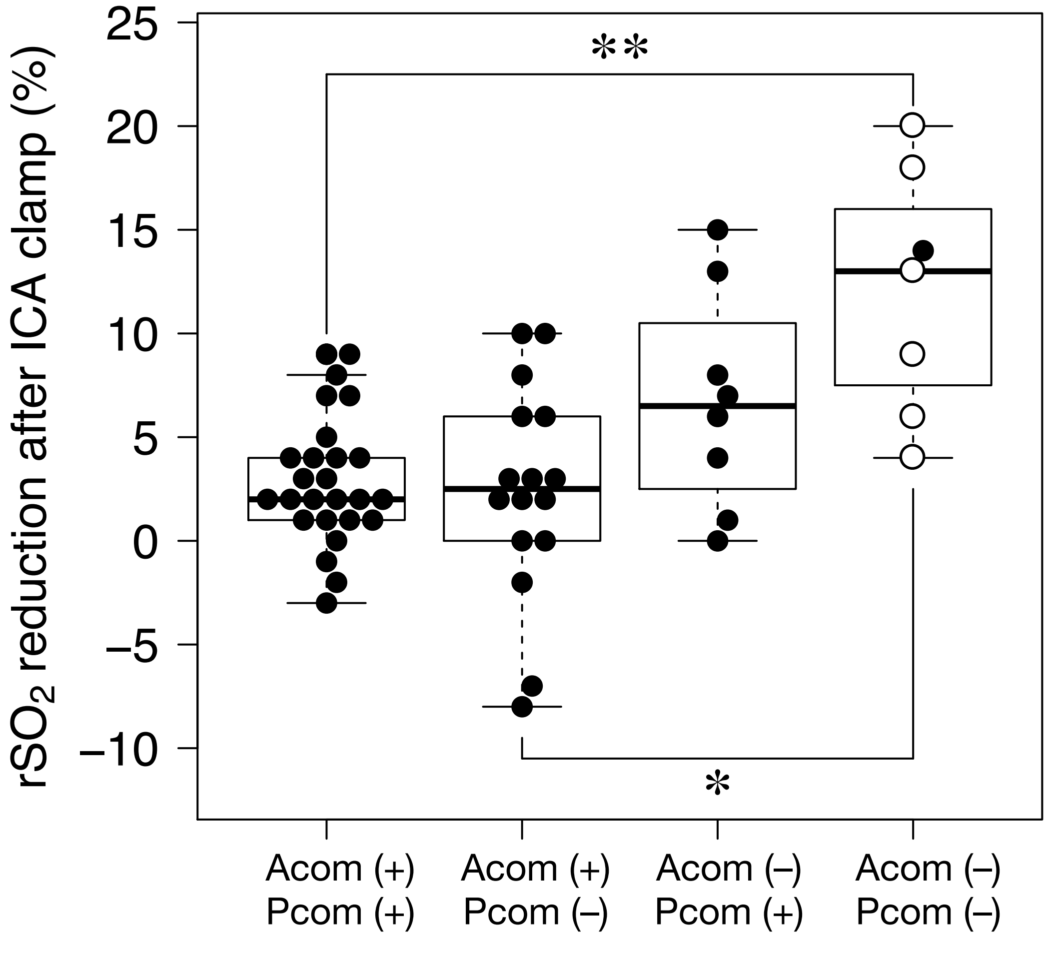

rSO2 reduction after ICA clamp (%)
25
20
15
10
5
0
−5
−10
**
*
Acom (+)
Pcom (+)
Acom (+)
Pcom (–)
Acom (–)
Pcom (+)
Acom (–)
Pcom (–)