Remodeling of Saccular Cerebral Artery Aneurysm Wall Is Associated With Rupture
Histological Analysis of 24 Unruptured and 42 Ruptured Cases

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Background and Purpose—The cellular mechanisms of degeneration and repair preceding rupture of the saccular cerebral artery aneurysm wall need to be elucidated for rational design of growth factor or drug-releasing endovascular devices.

Methods—Patient records, preoperative vascular imaging studies, and the snap-frozen fundi resected after microsurgical clipping from 66 aneurysms were studied. Immunostainings for markers of smooth muscle cell (SMC) phenotype, proliferation, and inflammatory cell subtypes and TUNEL reaction were performed.

Results—Unruptured (24) and ruptured (42) aneurysms had similar dimensions (median diameter in unruptured 6 mm; median in ruptured 7 mm; \( P = 0.308 \)). We identified 4 basic types of aneurysm wall that associated with rupture: (1) endothelialized wall with linearly organized SMCs (17/66; 42% ruptured), (2) thickened wall with disorganized SMCs (20/66; 55% ruptured), (3) hypocellular wall with either myointimal hyperplasia or organizing luminal thrombosis (14/66; 64% ruptured), and (4) an extremely thin thrombosis-lined hypocellular wall (15/66; 100% ruptured). Apoptosis, de-endothelialization, luminal thrombosis, SMC proliferation, and T-cell and macrophage infiltration associated with rupture. Furthermore, macrophage infiltration associated with SMC proliferation, and both were increased in ruptured aneurysms resected \(< 12 \text{ hours from rupture, suggesting that these were not just reactive changes.} \)

Conclusions—Before rupture, the wall of saccular cerebral artery aneurysm undergoes morphological changes associated with remodeling of the aneurysm wall. Some of these changes, like SMC proliferation and macrophage infiltration, likely reflect ongoing repair attempts that could be enhanced with pharmacological therapy. (Stroke. 2004;35:000-000.)

Key Words: cerebral aneurysm ■ inflammation ■ intracranial aneurysm ■ rupture

Saccular cerebral artery aneurysms (SCAAs) in the cerebral artery bifurcations are the most common cause of subarachnoid hemorrhage (SAH). Known SCAA risk factors include hypertension, smoking, heavy alcohol consumption, and female gender. Some SCAA cases are familial, with a linkage to 1q41.3 area in the Finnish population and to the 7q11 area in the Japanese population. The mechanisms of how these factors predispose to the formation or rupture of the SCAA wall are not known.

There are few reports about SCAA wall histology and the cellular mechanisms of SCAA rupture are unknown. Characterization of these mechanisms is mandatory for development of targeted treatment to prevent SCAA growth and rupture. Such a treatment could be delivered either systemically or by using coated endovascular devices such as stents or coils.

SCAA wall is subjected to increasing hemodynamic stress and likely becomes unstable and undergoes morphological changes before rupture. The cellular mechanisms of adaptation to increased hemodynamic stress in normal arterial wall are proliferation and luminal migration of smooth muscle cells (SMCs). These cellular mechanisms are partly controlled by cytokines released by inflammatory cells infiltrating the vascular wall. In addition to these 3 mechanisms, the SCAA wall is prone to form thrombosis lining of the luminal wall because of altered flow conditions. Organization of this thrombus lining thickens the wall.

Our aim was to characterize these cellular mechanisms in a series of human SCAA fundi (24 unruptured and 42 ruptured) resected after microsurgical clipping of the SCAA neck from patients that did not significantly differ in age or gender, or in aneurysm size or location.

Materials and Methods

Human SCAA Samples
SCAA samples were obtained during microsurgery by resecting the aneurysm sac distal to the clip closing the neck (J.H., M.N.,...
TABLE 1. Monoclonal Mouse Anti-Human Antibodies Used in the Study

<table>
<thead>
<tr>
<th>Antigen</th>
<th>Clone</th>
<th>Dilution</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD31 [PECAM 1 (platelet endothelial cell adhesion molecule)] 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD68 [macrophage marker] 27</td>
<td>PG-M1</td>
<td>1:200</td>
<td>DAKO</td>
</tr>
<tr>
<td>CD11b (MAC 1 [macrophage adhesion molecule] 1) 26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD163 (macrophage marker) 28</td>
<td>Ber-MAC3</td>
<td>1:200</td>
<td>DAKO</td>
</tr>
</tbody>
</table>

Department of Neurosurgery, Helsinki University Central Hospital; years 2000 to 2002; 220 aneurysms operated per year). The tissue samples were snap-frozen in liquid nitrogen and stored in -70°C. The study was approved by the ethics committee of the Departments of Neurology, Neurosurgery, Otorhinolaryngology, and Ophthalmology at the Helsinki University Central Hospital.

**Histology and Immunohistochemistry**
Snap-frozen tissue samples were cryosectioned at 4 μm. For histology, sections were stained with hematoxylin-eosin in Van Gieson methods. For immunohistochemistry, sections were first incubated for 30 minutes at room temperature in PBS with 1.5% horse serum, and then overnight at 4°C with a monoclonal mouse anti-human primary antibody (Table 1) at 1:200 or 1:100 dilution in PBS with 1.5% horse serum. The primary antibody was detected after blocking endogenous peroxidase by 20 minutes incubation in PBS with 0.1% hydrogen peroxide using the horseradish peroxidase–conjugated Vectastain anti-mouse kit (Vector Laboratories) and diaminobenzidine (Sigma-Aldrich). Sections were background stained with Gill’s hematoxylin (Vector Laboratories). Substitution of the primary antibody with an irrelevant monoclonal antibody (anti-bromodeoxyuridine, clone BU20A; DAKO) or with PBS with 1.5% horse serum served as negative controls. Anonymized sections from human tonsils served as positive controls. TUNEL stainings were performed using the peroxidase-conjugated Vectastain anti-mouse antibody (Roche Diagnostics). Anonymized sections from human tonsils served as positive controls. TUNEL stainings were performed using the peroxidase-conjugated Vectastain anti-mouse antibody (Roche Diagnostics).

**Histological Types of SCAA Walls**
SCAA walls of the 6 familial aneurysm patients did not differ from the 60 sporadic ones. Lack of elastic lamina was a common feature in the SCAAs studied. Atherosclerotic calcifications were seen in only 5 unruptured and 2 ruptured cases. However, pads of MH or MH-like disorganized wall structure occurred in both groups (Table 2). Four basic types of SCAA wall structure were distinguished (Figure 1A through 1D): type A (n=17), endothelialized wall with linearly organized SMC; type B (n=20), thickened wall with disorganized SMC; type C (n=14), hypocellular wall with either MH or OT; and type D (n=15), an extremely thin thrombosis-lined hypocellular wall. The prevailing wall type in the sample significantly associated (P=0.004) with rupture: 42% (7/17) in type A; 55% (11/20) in type B; 64% (9/14) in type C; and 100% (15/15) in type D. Symptoms suggestive of minor leaks before diagnosed SAH were recorded in 12 patients (29%), and minor leaks were associated with the D-type wall (P=0.011). Several aneurysm walls were heterogeneous with gradual change from types A or B to types C or D, mostly in the neck to fundus direction. The wall type was not associated with aneurysm size (P>0.384) or location (P=0.426) or presence of secondary pouches (P=0.795), but patients with B-type walls were younger (median 47 years) than patients with A-type (median 61 years) or C-type (median 58 years) walls (P=0.021).

**Thrombosis and Fibrosis**
Fresh thrombosis (Figure 1D) or OT (Figure 1C) lined the luminal aspect in 25% of unruptured and in 70% of ruptured SCAAs (Table 2). SMCs were seen more frequently in luminal OT of ruptured SCAAs (Figure 2, Table 2). OT often had areas so fibrotic that it was difficult to

**Clinical and Radiological Data**
Clinical data were collected from the patients’ medical records. Dimensions of the aneurysms were measured from preoperative vascular imaging studies: computed tomography, magnetic resonance angiography, or digital subtraction angiography.

**Statistics**
Statistics were calculated using the NCSS 2000 (NCSS Statistical Software). For categorical variables, proportions were calculated and \( \chi^2 \) independence test was used. For numeric variables, median and range were calculated, and Mann–Whitney U test and Kruskall–Wallis multiple comparison test were used. Logistic regression and multiple linear regression were used in multivariable analysis. \( \alpha \)-Level was 0.05.

**Results**
Patients with unruptured (n=24) or ruptured (n=42) SCAAs did not differ by age or gender (Table 2). The aneurysm neck and fundus sizes were similar (Table 2), and the most frequent locations were middle cerebral artery (67% in unruptured versus 41% in ruptured) and anterior communicating artery (AComA; 8% in unruptured versus 21% in ruptured). Secondary pouches in preoperative angiographies were seen in 30% of unruptured and in 67% of ruptured SCAAs (P=0.005).
distinguish them from neighboring intimal hyperplasia pads, and they are collectively termed as MH/OT areas in further analysis.

Factors Associated With Rupture
Ruptured SCAA walls showed increased de-endothelialization, fresh and organizing luminal thrombosis, proliferation ratio in MH/OT areas, apoptosis ratio outside MH/OT areas, and leukocyte infiltration (CD45, CD3, CD11b, CD68, and CD163) in both areas of the wall (Table 2, Figure 3). These histological changes were not associated with minor leaks. Leukocyte density in MH/OT areas and OT were independent risk factors in logistic regression analysis ($R^2=0.46; P=0.001$ for the model). Fibroblast antigen cells occurred equally in the walls of unruptured (39%) and ruptured (46%) SCAs.

Leukocyte Infiltration and Cell Proliferation in the SCAA Wall After Rupture
Of the 42 ruptured SCAs, 35 had been resected between 3.5 and 48 hours after rupture (Table 2). Proliferation ratio, T-cell density (CD3+), and macrophage density (CD163+) were increased in MH/OT areas already after 12 hours from rupture but remained stable in other areas of the wall (Figures 3 and 4). Density of CD11b+ cells and CD163+ cells in the MH/OT areas and density of CD68+ cells in other parts significantly associated with proliferation in MH/OT areas in multiple linear regression analysis ($R^2=0.82; P<0.001$ for the model).

Discussion
The cellular mechanisms of SCAA rupture have to be elucidated for development of locally delivered or systemic drug therapies. We describe in a series of 66 SCAA fundi morphological changes of the SCAA wall that correlate with rupture, association of inflammatory cell infiltration, and SMC proliferation with rupture, and association of macrophage infiltration with SMC proliferation in ruptured SCAA walls.

Morphological Changes in SCAA Wall Preceding Rupture
SCAs tend to grow over the years. Therefore, the SCAA wall has to undergo morphological changes that likely differ in unruptured and ruptured SCAs. In a previous series of 27 unruptured and 44 ruptured SCAA fundi, Kataoka et al found that thick intima-like walls are mostly unruptured, and very thin and degenerated walls with hyaline deposits mostly ruptured. Other previous studies on SCAA walls describe inflammatory cells, signs of complement activation, increased protease activity, variations in SMC phenotype, and apoptosis.

We identified 4 histological SCAA wall types that likely reflect consecutive stages (A through D) of wall degeneration proceeding to rupture. As Kataoka did, we also found

<table>
<thead>
<tr>
<th>TABLE 2. Patients and SCAs</th>
<th>Unruptured SCAs (n=24)</th>
<th>Ruptured SCAs (n=42)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>55 years (38–68)</td>
<td>52 years (13–76)</td>
<td>0.641</td>
</tr>
<tr>
<td>Gender</td>
<td>Males 29% (7/24)</td>
<td>Males 43% (18/42)</td>
<td>0.270</td>
</tr>
<tr>
<td>Familial background*</td>
<td>21% (5/24)</td>
<td>2% (1/42)</td>
<td>0.012</td>
</tr>
<tr>
<td>Patients with multiple SCAAs (≥2)</td>
<td>46% (11/24)</td>
<td>31% (13/42)</td>
<td>0.227</td>
</tr>
<tr>
<td>Patients with prior aneurysmal SAH</td>
<td>21% (5/24)</td>
<td>100% (42/42)</td>
<td></td>
</tr>
</tbody>
</table>

Median and range are given for continuous variables.
* $P<0.05$ ($\chi^2$ or Mann–Whitney U test).
that aneurysms with thin hyalinized walls (D-type wall in our series) were ruptured. However, in our series, also as many as 55% (11/20) of thick intima-like walls (B-type) had ruptured. This may reflect differences in Finnish and Japanese SCAA populations. Interestingly, in our series, B-type (thick intima-like) walls occurred in younger patients than A-type (organized) or C-type (hypocellular with luminal thrombosis) walls. Possible association between age and SCAA wall maintenance and repair capacity warrants further studies.

Maintenance and Repair of SCAA Wall

The wall of unruptured SCAs may remain intact for years. Thus, strong maintenance and repair mechanisms are mandatory. Our results suggest that before rupture, the SCAA wall becomes unstable and undergoes morphological changes that start at an undefined time interval before rupture. These changes reflect the effect of risk factors that predispose to rupture as well as the maintenance and repair mechanisms trying to prevent rupture. The factors distinguishing unruptured and ruptured SCAs in our series were: decellularization, apoptosis, and degeneration of wall matrix; de-endothelialization; thrombus organization; proliferation; and inflammatory infiltration. Most of these are features related to MH (ie, the mechanism of how generally the arterial wall responds to injury or hemodynamic stress). During MH formation, the SMCs that migrate from the vascular wall to the luminal surface secrete matrix metalloproteinases that destroy parts of the wall matrix and make the migration of SMCs possible. The morphological changes that result from the MH and matrix destruction are collectively referred to as remodeling of the vascular wall. Although MH is an adaptation mechanism of arteries to hemodynamic stress, in SAH patients, for undefined reasons, vascular wall remodeling was insufficient to prevent SCAA rupture. Paradoxically, in SCAs, remodeling might even facilitate rupture because of increased matrix proteolysis. It would be important to study aneurysms at a few weeks after rupture, but in our series, all but 6 aneurysms were clipped within 48 hours.

Inflammation in SCAA Wall

Ruptured SCAAs show inflammation. It is not known whether inflammation triggers the rupture of the SCAA wall.
causing SAH. However, it is known that infiltrating leukocytes, mainly T-cells and macrophages, stimulate SMC proliferation in areas of vascular wall thickening. We found that T-cell and macrophage infiltration associate with rupture, and furthermore, macrophage infiltration associates with SMC proliferation in the SCAA wall. Therefore, we hypothesize that in the SCAA wall, macrophages may stimulate SMCs to change phenotype and proliferate, thus promoting fibrosis. That SMC proliferation and T-cell and macrophage infiltration were increased in samples resected 12 hours from rupture suggests that these changes were, to some extent, present before rupture because in healthy arterial wall, they occur in response to injury during the first 24 hours or later (T-cell and macrophage infiltration as well as SMC proliferation).

Therapeutic Implications
Only few diagnosed SCAAs will occlude spontaneously. It is not known why luminal thrombosis, SMC migration, and vascular wall remodeling fail to prevent rupture and occlude untreated SCAA pouches. Systemic or locally delivered selected agents that stimulate SMC proliferation and migration to luminal thrombus might promote the occlusion. Our data suggest that inflammatory cell infiltration and SMC proliferation increase in the SCAA wall before rupture, and we hypothesize that they are part of the adaptation and repair mechanism of the SCAA wall. Locally delivered selected proinflammatory agents stimulating SMC proliferation and matrix synthesis might reinforce the SCAA wall. In addition, matrix metalloproteinase inhibitors that reduce proteolysis in mechanical arterial

Figure 3. The ratios of fibroblast-antigen+ proliferating and apoptotic cells from total cell number, and the density of inflammatory cells in the wall of unruptured and ruptured aneurysms. Median values and range are given for areas of MH/OT and other areas of the aneurysm wall. Significant differences (P<0.05; Mann-Whitney U test) between unruptured and ruptured aneurysm were found in: (1) the proliferation ratio in MH/OT areas, (2) the ratio of apoptosis in wall areas other than MH/OT, (3) the density of all inflammatory cell types in areas of MH/OT, and (4) the density of CD45+, CD163+, and CD11b+ cells also in other areas.
wall injury models\textsuperscript{33,34} might inhibit harmful matrix degradation in the SCAA wall and prevent rupture.

Acknowledgments

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