The introduction of the Guglielmi Detachable Coil system in the early 1990s ushered in the era of endovascular treatment for intracranial aneurysms. Thereafter, the role of endovascular therapy in the management of these lesions expanded with the introduction of balloon remodeling, stent-assisted coiling, and, most recently, flow-diverting stents. Middle cerebral artery (MCA) bifurcation aneurysms are situated peripherally and typically have a wide neck that incorporates the origin of one or both M2 segments. As a result of this configuration, MCA aneurysms largely remained in the domain of surgical repair. Increasingly, however, endovascular therapy has been used as an option for treating aneurysms in this location. The optimal treatment modality, however, is controversial. To provide information regarding surgical complication rates and treatment results for MCA bifurcation aneurysms, we reviewed the outcomes of 750 unruptured MCA aneurysms treated with open microsurgery by a single surgeon.

Methods

Patient Selection and Aneurysm Characteristics

All patients who were referred to the National Brain Aneurysm Center for treatment of an unruptured MCA aneurysm and underwent open surgical treatment of their lesion by a single surgeon between 1997 and 2015 were included in this retrospective case series based on a review of prospectively collected data. Preoperative catheter angiography was performed in all cases. Aneurysm size...
was measured based on maximum dome width using the following scale: small, < 10 mm; large, 10–25 mm; giant, > 25 mm. At our clinic, the principal decision to proceed with surgery is based on the estimated lifetime risk of aneurysm rupture compared to the anticipated risk of aneurysm repair, taking into consideration patient age, medical comorbidities, family or personal history of subarachnoid hemorrhage (SAH), psychological impact of aneurysm presence, and input from endovascular colleagues regarding the ease of endovascular treatment. All cases were included in a prospective database that included preoperative notes, operative reports, and postoperative outpatient notes. Imaging studies were reviewed for patients with a surgical complication. Lastly, to further investigate a comparison between surgical and endovascular treatment of “routine” MCA aneurysms, we performed a subgroup analysis of the small, saccular, noncoiled aneurysms.

Surgical Technique
We approached the aneurysms utilizing a standard pterional craniotomy, unless otherwise indicated. The intradural portion of all surgeries, including opening of the sylvian fissure, dissection, and clipping of the aneurysm, was performed under microsurgical magnification. No neuromonitoring was used, and all operations after 2001 (the most recent 701 surgeries) were performed without the inclusion of residents or fellows. Subtotal occlusion was undertaken when attempted complete occlusion resulted in narrowing of the parent artery or perforator compromise, or when calcification or atheroma precluded safe clip placement at the true aneurysm neck. When subtotal occlusion was performed, the area of the aneurysm that was left untreated was subsequently wrapped in all cases with muslin-type gauze, cotton, or Gore-Tex. Temporary clipping was only utilized for large or giant aneurysms to diminish aneurysm turgor and decrease the risk of aneurysm rupture during manipulation. Temporary clipping was used also in selected cases of previously coiled aneurysms during clipping of the aneurysm neck below the coils or during opening of the aneurysm to extract coils.

Aneurysm Occlusion on Digital Subtraction Angiography
Every patient underwent intraoperative digital subtraction angiography (DSA) by a nonblinded neuroradiologist to confirm appropriate clipping and to exclude the presence of local vascular compromise. Beginning in July 2010, the use of indocyanine green videoangiography (ICG) was added to provide complementary data in the remaining cases (n = 370). A comparison of ICG and DSA data was previously published for a portion of these cases and is not recorded here.7 For patients treated by clipping or bypass/sacrifice, the radiologist rated aneurysm occlusion on a percentage basis; in retrospective analysis, 100% was considered “complete occlusion/obliteration,” 90%–99% was considered “residual neck,” and 0%–89% was considered “incomplete occlusion.”

Perioperative Management and Follow-Up Characteristics
All surgeries were performed with the patient under general endotracheal anesthesia using barbiturate anesthe-
aneurysms, 9 (38%) were treated by primary clipping below the coil mass, 11 (46%) by distal bypass with vascular sacrifice, 2 (8%) by coil extraction followed by clipping, and 2 (8%) by simple wrapping.

Occlusion Rates and Complications

In aneurysms treated with clipping or bypass/sacrifice (n = 729), complete occlusion based on intraoperative angiographic examination was achieved in 671 aneurysms (92.0%), and residual neck was left in 58 aneurysms (8.0%). No aneurysms had incomplete occlusion (0.0%; Table 2). Intraoperative rupture occurred in 3 patients (0.4%). In one, the rupture was controlled by placing cotton at the rupture site, temporarily clipping the M1 segment, and then finishing the dissection; and in another the aneurysm dome was clipped preliminarily below the rupture site, allowing us to complete the exposure and clipping of the aneurysm neck. The remaining patient was given adenosine while the dissection was completed and the aneurysm clipped. Each patient recovered fully.

Complications

Treatment-related complications occurred in 20 patients (2.8%, Tables 2 and 3); 3 of these patients (15%)
experienced permanent deficits. One patient with a giant aneurysm measuring more than 4 cm developed delayed saphenous vein graft thrombosis, the result of which was a severe ischemic injury of his nondominant hemisphere. He survived with good cognitive function but required significant assistance with daily activities; his 30-day follow-up mRS score was 5, but it improved to 4 at 1 year. His postoperative course was also complicated by lower-extremity deep vein thrombosis. A perforating artery was injured in 2 patients: one patient was left with mild hemiparesis and the other with severe, permanent hemiparesis. One of the patients had an mRS score of 3 at the 30-day follow-up that improved to 2 at 6 months, and the other had an mRS score of 4 at the 30-day follow-up that improved to 3 at 6 months. Both injuries occurred in the setting of a very short M₁ segment.

Four patients had a single perioperative seizure within 1 hour of emerging from anesthesia. One required rethubation and remained intubated overnight. The other 3 patients were managed conservatively with lorazepam and underwent continuous electroencephalography (EEG) monitoring for 24 hours. After discharge, anticonvulsant therapy was continued for 3 months in 2 cases and 6 months in the other 2 cases; no patient required indefinite anticonvulsant therapy. Four patients noticed immediate transient neurological deficit (dysphasia in 2 cases and mild contralateral motor weakness in 2 cases), which was likely related to local retraction or venous injury. These 4 patients improved quickly and had recovered by their first postoperative visit, 7–10 days after surgery. Six patients developed deep venous thrombosis (DVT) during the 1st postoperative month. Two were managed with placement of an inferior vena cava filter, 2 with intravenous anticoagulation alone, and 2 with both. These 6 cases resolved without further complications.

Two patients (0.3%) developed wound infections that required intravenous antibiotics or surgical reexploration; infections that did not require these measures were not reported in our database. One patient with superficial cellulitis was treated with intravenous antibiotic therapy alone.

### TABLE 3. Summary of treatment-related complications

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Aneurysm Size (mm)</th>
<th>Presenting Symptoms</th>
<th>Complication</th>
<th>Treatment</th>
<th>Duration</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45, F</td>
<td>9</td>
<td>LE pain, swelling</td>
<td>DVT</td>
<td>IVC filter</td>
<td>6 wks; filter removed</td>
<td>Full recovery</td>
</tr>
<tr>
<td>2</td>
<td>59, F</td>
<td>6</td>
<td>LE pain, swelling</td>
<td>DVT</td>
<td>IVC filter</td>
<td>6 wks; filter removed</td>
<td>Full recovery</td>
</tr>
<tr>
<td>3</td>
<td>41, M</td>
<td>22</td>
<td>LE pain, swelling</td>
<td>DVT</td>
<td>Anticoagulation</td>
<td>6 mos</td>
<td>Full recovery</td>
</tr>
<tr>
<td>4</td>
<td>42, M</td>
<td>42</td>
<td>Hemiplegia, hemisensory loss, visual field defect, mild neglect</td>
<td>Delayed SVG thrombosis</td>
<td>None</td>
<td>Permanent</td>
<td>Good cognitive function; severe permanent disability requiring assistance w/ ADLs</td>
</tr>
<tr>
<td>5</td>
<td>55, F</td>
<td>15</td>
<td>LE pain, swelling</td>
<td>DVT</td>
<td>IVC filter &amp; anticoagulation</td>
<td>9 mos</td>
<td>Full recovery</td>
</tr>
<tr>
<td>6</td>
<td>67, M</td>
<td>12</td>
<td>LE pain, swelling</td>
<td>DVT</td>
<td>IVC filter &amp; anticoagulation</td>
<td>6 mos</td>
<td>Full recovery</td>
</tr>
<tr>
<td>7</td>
<td>39, F</td>
<td>10</td>
<td>Seizure</td>
<td>Postop seizures</td>
<td>Overnight intubation</td>
<td>6-mo anticonvulsant therapy</td>
<td>Resolved</td>
</tr>
<tr>
<td>8</td>
<td>54, F</td>
<td>6</td>
<td>Seizure</td>
<td>Postop seizures</td>
<td>Lorazepam</td>
<td>3-mo anticonvulsant therapy</td>
<td>Resolved</td>
</tr>
<tr>
<td>9</td>
<td>49, M</td>
<td>7</td>
<td>Seizure</td>
<td>Postop seizures</td>
<td>Lorazepam</td>
<td>3-mo anticonvulsant therapy</td>
<td>Resolved</td>
</tr>
<tr>
<td>10</td>
<td>55, F</td>
<td>11</td>
<td>Seizure</td>
<td>Postop seizures</td>
<td>Lorazepam</td>
<td>6-mo anticonvulsant therapy</td>
<td>Resolved</td>
</tr>
<tr>
<td>11</td>
<td>61, F</td>
<td>6</td>
<td>Dysphasia</td>
<td>Transient NDs</td>
<td>Decadron</td>
<td>1 wk</td>
<td>Resolved</td>
</tr>
<tr>
<td>12</td>
<td>58, M</td>
<td>7</td>
<td>Dysphasia</td>
<td>Transient NDs</td>
<td>Decadron</td>
<td>5 days</td>
<td>Resolved</td>
</tr>
<tr>
<td>13</td>
<td>49, F</td>
<td>9</td>
<td>Hemiparesis</td>
<td>Transient NDs</td>
<td>Decadron</td>
<td>1 wk</td>
<td>Resolved</td>
</tr>
<tr>
<td>14</td>
<td>50, F</td>
<td>8</td>
<td>Hemiparesis</td>
<td>Transient NDs</td>
<td>Decadron</td>
<td>3 days</td>
<td>Resolved</td>
</tr>
<tr>
<td>15</td>
<td>61, F</td>
<td>12</td>
<td>Hemiparesis</td>
<td>Perforating artery injury</td>
<td>None</td>
<td>Permanent</td>
<td>Mild, permanent</td>
</tr>
<tr>
<td>16</td>
<td>55, F</td>
<td>15</td>
<td>Hemiparesis</td>
<td>Perforating artery injury</td>
<td>None</td>
<td>Permanent</td>
<td>Severe, permanent</td>
</tr>
<tr>
<td>17</td>
<td>55, M</td>
<td>6</td>
<td>Cellulitis</td>
<td>Wound infection</td>
<td>Antibiotic</td>
<td>2 wks</td>
<td>Resolved</td>
</tr>
<tr>
<td>18</td>
<td>52, M</td>
<td>7</td>
<td>Wound fluctuance, redness</td>
<td>Wound infection</td>
<td>Surgical reexploration &amp; IV antibiotics</td>
<td>3 wks</td>
<td>Resolved</td>
</tr>
<tr>
<td>19</td>
<td>49, F</td>
<td>8</td>
<td>Temporalis fullness</td>
<td>Postop discomfort</td>
<td>Revision</td>
<td>Resolved</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>42, F</td>
<td>7</td>
<td>Temporalis fullness</td>
<td>Postop discomfort</td>
<td>Revision</td>
<td>Resolved</td>
<td></td>
</tr>
</tbody>
</table>

ADL = activity of daily living; IV = intravenous; IVC = inferior vena cava; LE = left eye.
The other patient underwent early reexploration with irrigation of the wound, and the bone flap was left in place. The patient received 3 weeks of intravenous antibiotic therapy, and the infection cleared.

Muscle Discomfort and Cosmetic Issues

While complaints of "fullness" and/or discomfort in the region of the temporalis muscle were common immediately after surgery, this complaint was transient in most patients. Eleven patients (1.5%) consistently reported fullness and discomfort to a level that required consultation with a plastic surgeon. In 9 of these patients, the discomfort was not bothersome enough to merit intervention. Two patients, however, underwent revision surgery in conjunction with a craniofacial plastic surgeon. In these cases, all hardware was removed, bony irregularities or defects were covered with bone cement, and the temporalis muscle was recontoured and resuspended. Although both patients stated that they were satisfied with the cosmetic outcome, 1 patient reported some fullness that produced an asymmetrical appearance compared with the unoperated side.

Subgroup Analysis of Small, Routine Aneurysms

We performed a subgroup analysis of the small, saccular, noncoiled aneurysms (n = 649). For these 649 aneurysms, complications occurred in 12 (1.8%) cases, although none resulted in lasting deficits; the follow-up mRS score was 0 in all cases (100%). However, it is important to consider the potential selection bias of these data when reflecting on these results.

Follow-Up and Patient Outcomes

Clinical follow-up was evaluated in all 716 patients within 30 days postoperation. The mean follow-up time was 8.5 years (range 6 months to 17 years). Cases with subtotal occlusion also underwent angiographic follow-up at 1, 2, and 5 years after surgery. During the follow-up period, no patients suffered bleeding from the treated aneurysm, and no patients died (0%). The average mRS score at follow-up was 0 (range 0–4); 713 patients had an mRS score of 0, 2 patients had a score of 2 or 3, and 1 patient had a score of 4 (Table 2). At follow-up, one fusiform M1 aneurysm had enlarged considerably and was therefore treated with an endovascular stent/coil approach.

Discussion

Management of MCA Aneurysms

As an "early adopter" of endovascular options, our center advocates strongly for the judicious use of minimally invasive therapies when outcomes are demonstrably comparable to or better than those achieved by microsurgery. Nevertheless, the use of endovascular therapy is expanding in many centers based on the assumption that minimizing invasiveness should correspondingly improve outcomes, even in the absence of evidence that such therapy is as safe as more traditional surgical options. It is therefore important to establish the durability of occlusion and the complication rates associated with both open surgical and endovascular treatment options. As a result, we are reporting our experience with the surgical management of MCA aneurysms in an unselected series of patients treated during the "endovascular era."

Multiple authors have described series of MCA aneurysms treated surgically, often as part of larger reported studies.1,5,6,8,12,17–22,26,27,29,31,32,34 In general, outcomes have been favorable, with excellent long-term durability associated with surgical repair of these lesions.21,28 In the hands of experienced microvascular surgeons managing intracranial aneurysms at high-volume centers, occlusion rates have exceeded 95%, while major complication rates have been less than 3%.28 The outcomes of the current series are consistent with these findings (Table 4).

Endovascular Treatment

Most of the large series describing the endovascular treatment of unruptured MCA aneurysms have also reported favorable results. In contrast to the surgical series, however, the rates of major complication have been significant. In a meta-analysis, Brinjikji et al. found that the overall permanent morbidity rate associated with endovascular therapy for unruptured MCA aneurysms was 5.1%, while the rate of complete or near-complete occlusion was 82%. In a more recent meta-analysis of 26 studies reporting 2207 aneurysms, Smith and colleagues found that the rate of complete occlusion for endovascular therapy slightly exceeded 50%.28 These findings are corroborated by those of individual series. Suzuki et al. treated 115 patients with MCA aneurysms, including 67 unruptured lesions, with detachable coils and achieved a complete occlusion rate of 46%. Complications included parent artery thrombosis (3.5%), thromboembolisms (3.5%), and aneurysm perforation (0.9%). Of the 67 unruptured aneurysms, distal emboli developed in 2 patients, one of whom suffered a delayed and fatal aneurysm rupture. Vendrell and coworkers treated 49 patients with unruptured MCA aneurysms with stent-assisted coiling. Intrastent clots formed in 10 patients (20%), resulting in 2 cases of permanent neurologic deficits. The overall rate of permanent neurologic morbidity was 4.3%. Furthermore, complete obliteration was achieved in 71% of their cases, and their rate of delayed recurrence was 14.6%. Quadros et al. treated 59 unruptured MCA aneurysms and achieved a 42% complete occlusion rate. Three aneurysms ruptured during treatment (6%), 10 thromboembolic events (20%) occurred, and 14.5% of the aneurysms recanalized over time. Bracadel et al. treated 152 MCA aneurysms in 140 patients. There were 3 perforations (2%) and 13 thromboembolic events (8.6%), including a 3.8% rate of embolic event in unruptured cases and 1 fatal stroke. In a series of 77 unruptured MCA aneurysms, one patient died, the permanent morbidity rate was 3%, and the recurrence rate was 20%. Outcomes

These results were used to suggest that MCA aneurysms can be treated using endovascular therapy safely and with low complication rates. However, the morbidity and mortality rates associated with these endovascular series consistently exceeded those reported by experienced microneurosurgeons. Nonetheless, endovascular treat-
ment may be preferable for certain populations and situations. When treatment is deemed advisable, endovascular therapy for MCA aneurysms can be given strong consideration in patients older than 70 years, when the aneurysm wall is calcified significantly, or when the geometry of the aneurysm is favorable for coiling or other endovascular therapy, such as narrow-necked aneurysms. However, for many MCA aneurysms, open microsurgery has demonstrably high occlusion rates and low complication rates, and should be considered a primary method of treatment.

Limitations

The principal limitation of this investigation is the retrospective nature of the data analysis, which introduces greater risk of confounding and bias. The individuals performing intraoperative angiography and determining posttreatment mRS scores were unblinded. Postoperative de novo aneurysm formation and minor infections were not reported in our database. Furthermore, the operations reported here were performed by a single, experienced microneurosurgeon and generally without the participation of residents, which may not be comparable to other large, academic centers and may limit the generalizability of the data.

Conclusions

Over the past 2 decades, endovascular therapy has emerged as an important treatment option for intracranial aneurysms, but it should be utilized only when it has complication rates comparable to those of open microsurgery. For unruptured MCA aneurysms, our report suggests that microsurgical clipping results in favorable outcomes more commonly than endovascular treatment, which should be reserved for older patients, those thought to be at high risk of complications from open surgery based on medical comorbidities or aneurysm-related factors, such as heavy wall atheroma, or aneurysms of particular morphologies. However, available data support the use of microsurgical therapy for management of most unruptured MCA aneurysms.

Acknowledgments

We acknowledge the nursing staff of the National Brain Aneurysm Center for their dedicated assistance with each of these patients, especially Jodi Lowary for her help in collecting and integrating patient data. We also acknowledge Superior Medical Experts for their editing and literature research support.

We received a grant from the United Hospital Foundation in support of this work.

References


Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: ES Nussbaum, Madison, Goddard, Lassig, LA Nussbaum. Acquisition of data: ES Nussbaum, Madison, Goddard, Lassig, LA Nussbaum. Analysis and interpretation of data: ES Nussbaum, Kallmes, LA Nussbaum. Drafting the article: all authors. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: ES Nussbaum. Administrative/technical/material support: Kallmes. Study supervision: ES Nussbaum, Kallmes.

Correspondence

Eric S. Nussbaum: National Brain Aneurysm Center, Minneapolis, MN. Inussbaum@comcast.net.