Microsurgical anatomy of cerebral revascularization. Part I: Anterior circulation

MASATOU KAWASHIMA, M.D., PH.D., ALBERT L. RHOTON JR., M.D., NECMETTIN TANRIOVER, M.D., ARTHUR J. ULM, M.D., ALEXANDRE YASUDA, M.D., AND KIYOTAKA FUJI, M.D., PH.D.

Department of Neurological Surgery, University of Florida, Gainesville, Florida; and Department of Neurosurgery, Kitasato University, School of Medicine, Kanagawa, Japan

Object. Revascularization is an important component of treatment for complex aneurysms that require parent vessel occlusion, skull base tumors that involve major vessels, and certain ischemic diseases. In this study, the authors examined the microsurgical anatomy of cerebral revascularization in the anterior circulation by demonstrating various procedures for bypass surgery.

Methods. Twenty-five adult cadaveric specimens were studied, using 3 to 40 magnification, after the arteries and veins had been perfused with colored silicone. The microsurgical anatomy of cerebral revascularization in the anterior circulation was examined with the focus on the donor, recipient, and graft vessels. The techniques discussed in this paper include the superficial temporal artery (STA)–middle cerebral artery (MCA), middle meningeal artery (MMA)–MCA, and side-to-side anastomoses; short arterial and venous interposition grafting; and external carotid artery/internal carotid artery (ICA)–MCA bypasses. Bypass procedures for cerebral revascularization are divided into two categories depending on their flow volume: low-flow and high-flow bypasses. A low-flow bypass, such as the STA–MCA anastomosis, is used to cover a relatively small area, whereas a high-flow bypass, such as the ICA–ICA anastomosis, is used for larger areas. Cerebral revascularization techniques are also divided into two types depending on the graft materials: pedicled arterial grafts, such as STA and occipital artery grafts, and free venous or arterial grafts, which are usually saphenous vein and radial artery grafts. Pedicled arterial grafts are mainly used for low-flow bypasses, whereas venous or arterial grafts are used for high-flow bypasses.

Conclusions. It is important to understand the methods of bypass procedures and to consider indications in which cerebral revascularization is needed.

Abbreviations used in this paper: ACA = anterior cerebral artery; AChA = anterior choroidal artery; CA = carotid artery; CCA = common CA; ECA = external CA; EC–IC = extracranial–intracranial; ICA = internal CA; MCA = middle cerebral artery; MMA = middle meningeal artery; OphA = ophthalmic artery; PCA = posterior cerebellar artery; PCoA = posterior communicating artery; RA = radial artery; STA = superficial temporal artery.

Materials and Methods

The focus of this paper is the microsurgical anatomy of cerebral revascularization, including donor and recipient vessels, and the techniques of revascularization, including STA–MCA, MMA–MCA, and side-to-side anastomoses; short arterial and venous interposition grafting; and ECA/ICA–M2 and ICA–ICA bypasses. We examined these vessels and techniques by using 25 adult cadaveric specimens and 3 to 40 magnification. Depending on the thickness of the vessel wall, 10-0, 8-0, 7-0, or 6-0 nylon thread (Ethicon, Inc., Somerville, NJ) was used for suturing. The saphenous vein and the radial artery were used as grafts for bypass procedures. The arteries and veins were perfused with colored silicone. The bone dissections were performed with the aid of a Midas Rex drill (Fort Worth, TX).

Results

Arterial Relationships

Table 1 shows the mean diameters of arteries frequently used for cerebral revascularization procedures.
Cerebral revascularization: anterior circulation

Internal Carotid Artery

The CCA divides into the ICA and ECA at the C2–3 level, below the mandibular angle. The cervical, petrous, and supraclinoid ICAs are sites of cerebral revascularization procedures and in this study their mean diameters were 8.57, 5.42, and 3.95 mm, respectively (Table 1). The cervical portion of the ICA is covered by the skin, superficial cervical fascia, platysma, deep fascia, anterior margin of the sternocleidomastoid muscle, and internal jugular vein. Dissection of these anatomical structures exposes the carotid triangle, which is formed by the posterior belly of the digastric, omohyoid, and sternocleidomastoid muscles. In the carotid triangle, the ICA begins at the bifurcation of the CCA, opposite the upper border of the thyroid cartilage, and runs perpendicularly upward, in front of the transverse processes of the upper three cervical vertebrae, to the carotid canal in the petrous portion of the temporal bone (Fig. 1A and B).

The petrous portion of the ICA courses within the carotid canal and ends at the point at which the artery enters the cavernous sinus. At the site where it enters the carotid canal, the CA is surrounded by a strong layer of connective tissue that makes it difficult to mobilize the artery. The roof of the carotid canal opens below the trigeminal ganglion near the neck of the mandible, and crosses over the posterior root of the mandible (Fig. 1C).

The supraclinoid segment of the ICA begins at the site where the artery emerges from the dura mater and enters the cranial cavity by passing along the medial side of the anterior clinoid process and below the optic nerve. It reaches the lateral side of the optic chiasm and bifurcates below the anterior perforated substance at the medial end of the sylvian fissure to give rise to the ACA and MCA. The supraclinoid segment of the ICA gives rise to three branches: the OphA, PCoA, and AChA. In addition, this segment has perforating branches including the superior hypophyseal artery (Fig. 1D).

External Carotid Artery

The ECA begins at the bifurcation of the CCA, in front of the ICA, and ascends backward to the space behind the neck of the mandible, where it divides into the STA and the maxillary artery. The mean diameter of the ECA was 5.75 mm (Table 1) in this study. The ECA is crossed by the hypoglossal nerve, the common facial and superior thyroid veins, and the digastic and stylohyoid muscles. The superior thyroid artery arises from the ECA just below the level of the greater cornu of the hyoid bone and ends in the thyroid gland. Because of its direction, the STA—the smaller of the two terminal branches of the ECA—appears to be a continuation of that vessel. The STA plays an important role as a donor vessel in cerebral revascularization. This artery has its origin in the substance of the parotid gland, behind the neck of the mandible, and crosses over the posterior root of the zygomatic process of the temporal bone. The mean diameter of the STA at the level of the zygoma was 1.93 mm in this study (Table 1). The STA divides into two branches: one frontal and the other parietal. The frontal branch (anterior temporal) runs tortuously upward and forward to the forehead, where it supplies the muscles, integument, and pericranium in this region, and anastomoses with the supraborbital and frontal arteries. The parietal branch (posterior temporal) is larger than the frontal branch; it curves upward and backward on the side of the head, lying superficial to the temporal fascia. This artery anastomoses with its counterpart on the opposite side and with the posterior auricular and occipital arteries (Fig. 1B).

Middle Cerebral Artery

The M1 and M2 segments of the MCA are sites of cerebral revascularization procedures. The M1 segment includes the trunks that lie on and supply the insula. This segment begins at the genu, where the MCA trunk passes over the limen insulae and terminates at the circular sulcus of the insula. The greatest branching of the MCA occurs distal to the genu at the site at which these trunks cross the anterior part of the insula. The M3 branches are used for bypass procedures, especially for high-flow bypasses. Important factors to consider in selecting an artery for a procedure are its diameter, the length of artery available on the cortical surface, and the perforating arteries that arise from this segment and lead to the basal ganglia. The average diameter of the largest branch near the central sulcus of the insula was 1.76 mm (Table 1).

The M3 segment is composed of branches leading to the lateral convexity. These branches begin at the surface of the sylvian fissure and extend over the cortical surface of the cerebral hemisphere. The largest cortical artery is the temporoparietooccipital artery. Nearly two thirds of these vessels are 1.5 mm or larger in diameter and 90% are 1 mm or wider. The smallest cortical artery is the orbitofrontal artery; approximately one quarter of these vessels are 1 mm or larger in diameter. In the present study the mean diameters of

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Diameters of arteries frequently used for cerebral revascularization procedures in the anterior circulation*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artery</td>
<td>Mean Diameter (mm)</td>
</tr>
<tr>
<td>ICA</td>
<td></td>
</tr>
<tr>
<td>cervical segment</td>
<td>8.57 ± 1.34</td>
</tr>
<tr>
<td>petrous segment</td>
<td>5.42 ± 0.68</td>
</tr>
<tr>
<td>supraclinoid segment</td>
<td>3.95 ± 0.56</td>
</tr>
<tr>
<td>ECA</td>
<td></td>
</tr>
<tr>
<td>cervical portion</td>
<td>5.75 ± 0.94</td>
</tr>
<tr>
<td>STA</td>
<td>at level of zygoma</td>
</tr>
<tr>
<td>MCA</td>
<td></td>
</tr>
<tr>
<td>M1 segment (largest branch near central sulcus)</td>
<td>1.76 ± 0.36</td>
</tr>
<tr>
<td>M2 segment (largest branch in area)</td>
<td>0.94 ± 0.40</td>
</tr>
<tr>
<td>frontal branch</td>
<td>1.19 ± 0.32</td>
</tr>
<tr>
<td>parietal branch</td>
<td>1.22 ± 0.23</td>
</tr>
<tr>
<td>M3 segment (largest branch in area)</td>
<td>1.36 ± 0.24</td>
</tr>
<tr>
<td>temporal branch</td>
<td>1.22 ± 0.23</td>
</tr>
<tr>
<td>parietal branch</td>
<td>1.55 ± 0.12</td>
</tr>
</tbody>
</table>

* Values are expressed as means ± standard deviations.
Cerebral revascularization: anterior circulation

the largest M, in the parietal, temporal, and frontal areas were 1.36, 1.22, and 1.19 mm, respectively (Table 1). The central sulcal artery is the largest branch leading to the frontal lobe, and the angular artery is the largest branch leading to the parietal lobe. The temporopolar and posterior temporal arteries are the largest branches extending to the temporal lobe. The minimum length of a cortical artery needed to complete a bypass is 4 mm. The angular, posterior parietal, and temporopolar arteries have the longest segments on the cortical surface, and the orbitofrontal and temporopolar arteries have the shortest cortical segments (Fig. 1E and F).

Anterior Cerebral Artery

At the ACoA the ACA divides into two parts, proximal (A1 segment) and distal (A2–A5 segments). The A1 segment of the ACA is the dominant site of cerebral revascularization procedures, including side-to-side anastomosis and short arterial and venous interposition grafting. The average diameters of the A1, A2, and A3 segments in this study were 2.35, 1.98, 1.94, and 1.55 mm, respectively (Table 1). The pericallosal artery is the portion of the ACA that lies distal to the ACoA and is constantly present. The pericallosal artery ascends in front of the lamina terminalis to pass into the interhemispheric fissure (A segment). Above the lamina terminalis, the artery makes a smooth curve around the genu of the corpus callosum (A segment) and then courses backward above the corpus callosum in the pericallosal cistern (A and A segments).

The callosomarginal artery is defined as the artery that courses in or near the cingulate sulcus and gives rise to two or more major cortical branches. When the callosomarginal artery is well formed, it lies in the cingulate sulcus above the cingulate gyrus and follows a course roughly parallel to that of the pericallosal artery. Its origin varies from just distal to the ACoA to the level of the genu of the corpus callosum. Its origin frequently is found at the A3 segment, followed by the A4 segment and the A5oA. The size of the pericallosal artery distal to the origin of the callosomarginal artery varies inversely with the size of the callosomarginal artery (Fig. 1G and H).

Types of Grafts

Artery Graft: Radial Artery. The RA appears, from its direction, to be the continuation of the brachial artery, but it is smaller in caliber than the ulnar artery. Beginning at the bifurcation of the brachial artery, just below the bend of the elbow, the RA passes along the radial side of the forearm to the wrist and then winds backward around the lateral side of the carpus, beneath the tendons of the abductor pollicis longus and extensor pollicis longus muscles. In the upper third of its course in the forearm, the RA lies between the brachioradialis and pronator teres muscles and, in the lower two thirds of its course, it lies between the tendons of the brachioradialis and flexor carpi radialis muscles. The superficial branch of the radial nerve is close to the lateral side of the artery in the middle third of its course.

Before the dissection of the RA, an Allen test is necessary to check the circulation of collateral blood to the territory of this vessel. The RA is exposed at the wrist, where it is located beneath the skin. One can trace the artery proximally in the forearm, between the brachioradialis and the pronator teres muscles, up to the bifurcation of the brachial artery. Branches joining the artery are subjected to ligation or bipolar cautery. Heparinized saline solution is used to wash out blood inside the vessel and to check for
leaks. The harvested RA graft is placed in heparinized saline (Fig. 2A–C).

Vein Graft: Great Saphenous Vein. In the superficial veins of the lower extremity, the great saphenous vein has been used as a graft for cerebral revascularization. The great saphenous vein, the longest vein in the body, has its origin in the medial marginal vein of the dorsum of the foot and ends in the femoral vein approximately 3 cm below the inguinal ligament. The vein ascends along the medial side of the leg in relation to the saphenous nerve. The vein runs upward behind the medial condyles of the tibia and femur and along the medial side of the thigh; passing through the fossa ovalis, the vein ends in the femoral vein. The vein is harvested from the leg or thigh, depending on the caliber of the graft required, with care taken to avoid vascular injury and potential thrombosis. The incision is begun 1 cm anterior and 1 cm rostral to the medial malleolus (dotted circle in D), and the vein is located in the subcutaneous tissue. Brachiorad. = brachioradialis; Car. = carpi; Flex. = flexor; Gr. = great; Rad. = radialis; Uln. = ulnar.
Cerebral revascularization: anterior circulation

The vein is harvested from the leg or thigh, depending on the caliber of the graft required, by using care to avoid vascular injury and potential thrombosis. The incision is begun 1 cm anterior and 1 cm rostral to the medial malleolus, and the vein is located in the subcutaneous tissue. The vein is traced superiorly toward the medial side of the knee for 15 to 20 cm as needed. Branches joining the vein are either ligated or occluded using small clips. Before the saphenous vein is dissected, it is marked superficially with a skin marker to avoid later kinking. After complete dissection of the saphenous vein, the vessel is ligated proximally and distally, sectioned, and removed. Heparinized saline solution is used to wash out the blood inside the vessel and to check for leaks. The harvested saphenous graft is placed in heparinized saline (Fig. 2D–F).

Procedures for Cerebral Revascularization

The STA–MCA Anastomosis. An STA–MCA anastomosis is the most frequently performed anastomotic procedure in the anterior circulation. The patient is positioned supine, with the head turned so that the side of the bypass is easily accessible. The STA courses in the subcutaneous tissue above the galea (Fig. 3A). The outline of the STA is determined either by palpation or by using a portable Doppler device. The severed end of the STA is stripped of its fascial layer, and a 7- to 8-mm portion of the vessel is exposed (Fig. 3B). Once dissection of the STA has been completed, the temporal muscle and fascia are incised at the site of the craniotomy (Fig. 3C and D). Removal of the bone flap and dura mater exposes the cerebral cortex, where the anastomosis is performed. The frontal branch of the STA courses above the frontotemporal region, whereas the parietal branch of the STA passes above the parietotemporal region (Fig. 3E). The recipient artery, which is wider than 1 mm and has a segment measuring at least 6- to 8-mm long for microanastomosis, is chosen according to its supply area. One or two small branches from the recipient vessel may need to be coagulated and sacrificed. A colored background material is placed beneath the recipient artery. The tip of the STA is then cut, making a fish-mouth incision suitable for the anastomosis site. The recipient vessel is prepared by placing temporary clips across it and performing a small arteriotomy. After two stay sutures have been placed, anastomosis of the STA to the recipient vessel is performed using interrupted 10-0 nylon sutures (Fig. 3F and G).

The MMA–MCA Anastomosis. The MMA is anastomosed to the MCA in this procedure. After a frontotemporal craniotomy has been performed, the MMA is dissected from between the dural leaves. Anastomosis is accomplished using interrupted 10-0 nylon sutures (Fig. 4A–D).

The Side-to-Side (MCA–MCA and ACA–ACA) Anastomosis. This procedure is mainly used for cerebral revascularization of MCA branches and the distal ACA (A1 segment), combined with occlusion of their proximal branch vessels. Arteriotomies, 4 mm in length, are made in both donor and recipient arteries. The most difficult procedure is to make a tight suture on a back wall. After two stay sutures have been placed in the distal and caudal edges of the arteriotomies, the back wall is sutured in a continuous running fashion from the intravascular side. The anterior wall is subsequently closed using interrupted sutures (10-0 nylon). Occlusion of the proximal vessel is then completed. The distal portion of the artery that lies beyond the occlusion site is supplied by the adjacent artery (Fig. 5A–F).

Short Arterial Interposition Graft Anastomosis. The STA or the occipital artery is used for an arterial graft. A section of STA graft approximately 4 cm long is dissected from a skin flap, and both severed ends of the STA are stripped of the fascial layer. The graft is anastomosed between the bilateral A1 segments by using interrupted sutures (10-0 nylon). Then, the right pericallosal and calloso marginal junction is occluded. The distal portion of the right pericallosal artery is supplied by the left pericallosal artery (Fig. 6A and B).

Short Venous Interposition Graft Anastomosis. In this technique, a short vein graft is used to connect the donor and recipient arteries. Cerebral revascularization is performed using a short saphenous vein graft or a superior temporal vein graft, between 5 and 10 cm in length, which extends from the STA trunk anterior to the ear to the M1 or M2 segment. An end-to-side anastomosis of the vein to the recipient artery is performed using 10-0 nylon interrupted sutures. After completion of the anastomosis at the distal end, an end-to-end anastomosis of the vein to the STA trunk immediately above the zygoma is performed using 8-0 nylon interrupted sutures (Fig. 6C and D).

Cervical ECA/ICA–M1 Anastomosis. Either a saphenous vein graft or an RA graft is used for this bypass procedure. The ECA, ICA, and ECA are exposed in the carotid triangle by making a cervical incision along the anterior aspect of the sternocleidomastoid muscle. The zygomatic arch is drilled to fashion a conduit for the graft when it is placed in a preauricular position. After the craniotomy, a wide dissection of the sylvian fissure is performed. The MCA trunk is identified and the secondary branches are dissected at their origin. The secondary vessel, which is thick and has the least number of side branches, is chosen and mobilized for the anastomosis. The diameter of the vessels in the insular area is normally larger than 1 mm. Care should be taken to avoid damaging the lenticulostriate perforating vessels that extend from the M1 branches. The main trunk of the MCA is dissected distal to the lenticulostriate perforating vessels, and its branches are also dissected. The distal anastomosis between the M1 segment and the graft is then performed in an end-to-side fashion by using interrupted 10-0 nylon sutures. After completion of the distal anastomosis, the cervical ECA is occluded proximally and distally. The graft is pulled down through the subcutaneous tunnel. An arteriotomy, approximately 6 to 8 mm in length, is made on the ECA. The graft is anastomosed to the artery in an end-to-side fashion by using 7-0 nylon sutures (Fig. 7A–C).

Petrous ICA–Superior Sigmoid ICA Anastomosis. After the petrosal craniotomy, the sylvian fissure is opened widely. The sphenoid ridge, anterior clinoid, and proximal optic canal are drilled away. The distal dural ring is cut to provide room to place a clip on the ICA proximal to the OphA. A sufficiently long piece of the ICA is then available between the OphA and the PCoA for use in anastomosing a saphenous vein graft. Exposure of the petrous segment of the ICA is performed extradurally under the middle fossa dura mater. The dura is elevated along the course of the MMA to the foramen spinosum. The MMA is divided and exposure is continued medially and anteriorly to the foramen ovale. A small area of bone posterior to the third branch of the trigeminal nerve and medial to the foramen spinosum is
FIG. 3. Photographs of cadaveric specimens demonstrating an example of a low-flow bypass, an STA–MCA anastomosis. A and B: An STA–MCA anastomosis is the most common operative procedure performed to create a low-flow bypass. The outline of the STA is determined either by palpation or by using a portable Doppler device. The severed end of the STA is stripped of its fascial layer and a 7- to 8-mm portion of the vessel is exposed. C and D: The STA divides into two branches, frontal and parietal. Once dissection of the STA is completed, the temporal muscle and fascia are incised at the site of the craniotomy. E: Removal of the bone flap and the dura mater exposes the cerebral cortex, where the anastomosis is performed. The anterior branch of the STA courses above the frontotemporal region, whereas the posterior branch of the STA passes above the parietotemporal region. F and G: The recipient artery, whose diameter is larger than 1 mm and has a segment at least 6 to 8 mm long that can be used for microanastomosis, is chosen according to its supply area. One or two small branches from the recipient vessel may need to be coagulated and sacrificed. The tip of the STA is cut, making a fish-mouth incision suitable for the anastomosis site. The recipient vessel is prepared by placing temporary clips across the vessel and performing a small arteriotomy. After two stay sutures have been placed, anastomosis of the STA to the recipient vessel is performed using 10-0 nylon interrupted sutures (arrows in F). Sphen. = sphenoid; STA = superficial temporal artery.
drilled away to expose a portion of the petrous ICA that is longer than 1 cm. The Eustachian tube and the tensor tympani muscle are identified and preservation of these structures is attempted. The saphenous vein is anastomosed to the petrous segment of the ICA in an end-to-side or end-to-end fashion between temporary clips. Interrupted sutures are made using 8-0 nylon thread. The other end of the saphenous vein graft is then anastomosed to the ICA in an end-to-side or end-to-end fashion between the OphA and the PCoA by using an 8-0 or a 10-0 suture, depending on the wall thicknesses of the ICA and vein graft. Anastomosis at this site is often difficult because a sclerotic change in the arterial wall is frequently observed in the supraclinoid segment of the ICA (Fig. 8A–D).

Cervical ICA–Petrous ICA Anastomosis. The cervical segment of the ICA in the carotid triangle and the horizontal segment of the petrous ICA are exposed as previously described. An RA graft is passed from the cervical area beneath the subcutaneous tissue on the zygomatic arch toward the petrous ICA. The proximal end of the RA graft is anastomosed to the cervical ICA by using interrupted sutures (7-0 nylon). The distal end of the saphenous vein graft is then anastomosed in an end-to-side or end-to-end fashion to the cervical ICA by using interrupted sutures (7-0 nylon). The distal end of the saphenous vein graft is then anastomosed in an end-to-side or end-to-end fashion to the supraclinoid ICA by using interrupted sutures (8-0 or 6-0 nylon). Frequently, the intima of the supraclinoid portion of the ICA is atherosclerotic (Fig. 8F).

Bonnet Bypass. In the absence of an available ipsilateral donor artery in a patient requiring cerebral revascularization, an anastomosis between the contralateral STA or ICA/ECA and a branch of the MCA (M2 or M4 segment) should be performed using a saphenous vein or an RA graft. After a left frontotemporal craniotomy, the saphenous vein graft is anastomosed to the contralateral ICA. The graft is then placed over the skull through the subcutaneous tunnel and is anastomosed to the left M2 or M4 segment (Fig. 9A–D).

Discussion
Cerebral revascularization is an important procedure in the treatment of complex intracranial aneurysms, cranial base tumors, and certain ischemic diseases. In this study, we examined microsurgical procedures for cerebral revascularization in the anterior circulation and demonstrated each procedure by using cadaveric specimens. This knowledge is helpful not only for surgeons but also for neurologists, neuroradiologists, and other physicians so that they may understand the methods of cerebral revascularization.

Bypass Procedures. Bypass procedures for cerebral revascularization are divided into two categories depending on
their flow volume: low-flow and high-flow bypasses. The low-flow bypass includes the STA–MCA, MMA–MCA, side-to-side, and arterial and venous short interposition graft anastomoses. These techniques are normally used to cover a relatively small area, where large volumes of blood are not necessary because of the small caliber of the donor vessel and the low inflow from the terminal branch. Since the STA–MCA anastomosis was introduced for EC–IC M. Kawashima, et al.

FIG. 5. Photographs of cadaveric specimens showing a low-flow bypass provided by side-to-side anastomosis. A–C: The M$_1$ segments of the MCA. A side-to-side anastomosis is performed between the distal M$_2$ segments (dotted area) in preparation for the proximal occlusion of the M$_2$ segment. The side-to-side anastomosis between the distal M$_2$ segments has been completed (arrowhead in B), followed by occlusion of the proximal M$_1$ segment performed using permanent clips (arrow in B). The distal portion of the M$_2$, which lies beyond the occlusion site, is supplied by the adjacent M$_1$ (dotted arrows in C) through the anastomotic site (arrowhead in C). D–F: The A$_3$ segments of the ACA. A side-to-side anastomosis is performed between the A$_3$ segments of the ACA (arrowhead in E), in preparation for the proximal occlusion of the right A$_2$ segment. The distal portion of the right M$_2$ segment, which lies beyond the occlusion site (solid arrow in F) is supplied by the left A$_3$ segment (dotted arrows in F) through the anastomotic site (arrowhead in F).
Cerebral revascularization: anterior circulation

Fig. 6. Photographs of cadaveric specimens showing a low-flow bypass provided by a short interposition graft anastomosis. A and B: Short arterial interposition graft anastomosis. A section of the STA approximately 5 cm long is dissected from a skin flap and both severed ends of the piece of STA are stripped of the fascial layer. The graft (black arrowheads in B) is anastomosed between the bilateral A3 segments by using interrupted sutures (10-0 nylon). Following this, the right pericallosal and callosomarginal junction is occluded (arrow in B). The distal portion of the right pericallosal artery is supplied by the left pericallosal artery through the anastomotic sites (white arrowheads in B). C and D: Short venous interposition graft anastomosis. Cerebral revascularization is performed using a short saphenous vein graft or a superior temporal vein graft 5 to 10 cm in length and extending from the STA trunk anterior to the ear to the M2 segment (arrows). An end-to-side anastomosis of the vein to the recipient artery is performed using 10-0 nylon interrupted sutures. After completion of the anastomosis at the distal end, an end-to-end anastomosis of the vein to the STA trunk immediately above the zygoma is performed using 8-0 nylon interrupted sutures.

anastomotic procedures,14,56 it has played an important role in cerebral revascularization. Some modifications of this technique, such as a double-barrel STA–MCA bypass connection26 and STA–M2 anastomosis,13 have been reported to increase flow from the bypass. The site of an MCA anastomosis for an MCA branch or trunk should be selected only after a careful review of the angiograms by considering the desirable blood flow to supply the ischemic area. Other important factors to consider in the selection of a cortical artery for this procedure are its diameter and the length of artery available on the cortical surface. In a previous study the largest cortical artery was found to be the temporooccipital artery.17 In addition, Chater and associates9 found a cortical artery with a diameter larger than 1.4 mm in the angular zone in 100% of hemispheres. In the present study, we also had similar results regarding the diameter of the M1 segment. Arteries over the tip of the temporal lobe and the frontal lobe were considerably smaller. Side-to-side anastomosis is used when extracranial vessels are injured, atherosclerotic, or very small in caliber. It eliminates the require-
ment of an extra vessel to be harvested and the need to perform two anastomoses. This procedure is especially suitable for revascularization of the ACA (pericallosal artery) because that artery is located deep inside the frontal interhemispheric fissure, away from pedicled arteries such as the STA and the occipital artery.

The MMA could be a potential donor artery for cerebral revascularization when the STA is unavailable because of atresia, surgery, injury, infection, or

Fig. 7. Photographs of cadaveric specimens showing an example of a high-flow bypass represented by a cervical ECA/ICA–M2 anastomosis. A–C: Either a saphenous vein graft or an RA graft is used for this procedure. The CCA, ICA, and ECA are exposed in the carotid triangle. The zygomatic arch is drilled to fashion a conduit for the graft when it is placed in the preauricular position. After the cranietomy, a wide dissection of the sylvian fissure is performed. The MCA trunk is identified and its secondary branches are dissected at their origins. The secondary vessel, which is thick and has the least number of side branches, is chosen and mobilized for the anastomosis. The main trunk of the MCA is occluded distal to the lenticulostriate perforating arteries, and its branches are also occluded. The distal anastomosis is then performed in an end-to-side fashion by using interrupted 10-0 nylon sutures (arrowhead in Fig. B). After completion of the distal anastomosis, the cervical ECA or ICA is occluded proximally and distally. An arteriotomy, approximately 6 to 8 mm long, is made on the arterial surface. The graft is anastomosed to the artery in an end-to-side fashion by using 7-0 nylon sutures.

Fig. 8. Photographs of cadaveric specimens demonstrating ICA–ICA high-flow bypasses. A–D: Petrous ICA–supraclinoid ICA anastomosis. The sphenoid ridge, anterior clinoid, and proximal optic canal are drilled away. The distal dural ring is cut to provide room to place a clip on the ICA proximal to the OphA. A sufficient portion of the ICA between the OphA and the PcoA is available for anastomosing a graft. Exposure of the petrous segment of the ICA is performed extradurally under the middle fossa dura. A small area of bone posterior to the third branch of the trigeminal nerve and medial to the foramen spinosum is drilled away to expose a portion of the petrous ICA longer than 1 cm. The Eustachian tube and the tensor tympani muscle will be identified and their preservation will be attempted. The saphenous vein is anastomosed to the petrous segment of the ICA in an end-to-side or end-to-end fashion between temporary clips. Interrupted sutures are made using 8-0 nylon thread. The other end of the saphenous vein graft is then anastomosed to the ICA in an end-to-side (on the right side) or an end-to-end (on the left side) fashion between temporary clips by using either an 8-0 or a 10-0 suture. Arrowheads in B, C, and D indicate anastomotic sites. E: Cervical ICA–petrous ICA anastomosis. The cervical segment of the ICA in the carotid triangle and the horizontal segment of the petrous ICA are exposed. An RA graft is passed from the cervical area toward the petrous ICA. The proximal end of the saphenous vein graft is anastomosed in an end-to-side fashion to the cervical ICA by using interrupted sutures (7-0 nylon). The distal end of the saphenous vein graft is then anastomosed in an end-to-side fashion to the petrous ICA by using interrupted sutures (8-0 nylon). F: Cervical ICA–supraclinoid ICA anastomosis. The supraclinoid segment of the ICA can be used as the recipient vessel when the MCA is not suitable for anastomosis. The cervical and supraclinoid segments of the ICAs are exposed. The proximal end of the saphenous vein graft is anastomosed in an end-to-side or end-to-end fashion to the cervical ICA, and the distal end of the saphenous vein graft is anastomosed in an end-to-side fashion to the supraclinoid ICA by using interrupted sutures (8-0 or 6-0 nylon). Frequently, the intima of the ICA in the supraclinoid portion is atherosclerotic. Arrowheads in E and F indicate anastomotic sites. Arrows in E and F indicate the site of inset. Ophth. = ophthalmic; P1, P2 = segments of the PCA.
Cerebral revascularization: anterior circulation
embolization. If the MMA is dilated in a pathological state to meet demand, the procedure would be easier than under normal conditions. A side-to-side anastomosis is rarely performed by neurosurgeons, although it is a routine procedure in cardiovascular surgery. A narrow and deep operative field and a difficult microsurgical procedure may prevent neurosurgeons from using this technique easily. Usually, a running suture is used for both far and near suture lines. The size of the orifice should be larger than twice the vessel diameter. Bederson and Spetzler also reported a patient with a giant proximal MCA aneurysm who was treated successfully by performing a side-to-side anastomosis of the anterior temporal artery to a secondary trunk of the MCA. Short arterial or venous interposition grafts are an alternative to a long vein graft in cases in which a relatively small area needs to be supplied. This procedure should be planned if a branch of the STA or the occipital artery displays atherosclerotic changes and the proximal branch of the recipient vessel is not available for side-to-side anastomosis because of stenosis or occlusion. The pressure difference between the donor and recipient vessels is not as great as that afforded by saphenous vein or RA grafts. Therefore, to prevent later graft occlusion short interposition grafts should not be long. The high-flow bypass includes the ECA/ICA–MCA and ICA–ICA anastomoses, which are suitable for supplying large areas when long saphenous vein or RA grafts are used. The high-flow bypass supplies enough blood flow to cover the entire MCA and ACA territories supplied by the ICA. This procedure is usually more difficult than that of the low-flow bypass because it requires handling high-flow vessels in a narrow and deep operative field. Anastomotic sites include the cer-

![Fig. 9. Photographs of cadaveric specimens demonstrating a high-flow bypass, the bonnet bypass. A and B: A saphenous vein graft is anastomosed to the left M2 segment in the sylvian fissure (white arrowhead in B). C and D: The graft is placed over the skull through the subcutaneous tunnel (black arrowheads) and anastomosed to the right ICA.](image)
Cerebral revascularization: anterior circulation

ical ICA and ECA, the petrous ICA, the supraclinoid ICA, and the M₂ segment. The M₂ segment is located in the sylvian fissure on the insular cortex; therefore, bypass surgery is more easily performed at this site than at other sites in a high-flow bypass. The mean diameter of the largest M₂ segment near the central sulcus of the insula was 1.76 mm in this study. Umansky, et al., also reported that the diameter of the M₂ in the insular area is larger than 1 mm and, in the case of secondary trunks, it is usually larger than 2 mm, thus making it suitable for most cerebral revascularization procedures. The ECA is used as a donor vessel if there is no collateral circulation in the high-flow bypass, whereas the ICA is used as a donor vessel if there is at least some collateral flow and the ICA can be safely occluded temporarily. The bonnet bypass is performed either for a low-flow or high-flow bypass, depending on the donor artery.26,40

On the other hand, cerebral revascularization techniques are divided into two types, depending on whether the graft materials are pedicled arterial grafts, such as STA and occipital artery grafts, or free venous or arterial grafts, which are usually saphenous vein grafts. The pedicled arterial grafts are mainly used for low-flow bypasses, whereas the free venous or arterial grafts are used for high-flow bypass. For patients in whom both the STA and the occipital artery are affected by atheromatous disease or in whom the anastomosis site is far from the pedicled graft, however, free venous or arterial grafts are used in low-flow bypasses as described previously.32,33,38,43 The long saphenous vein graft is usually used as an interposition graft in high-flow EC–IC bypass surgery. The flow through the saphenous vein graft is enough to prevent ischemia in patients with an isolated ICA and no collateral vessels. On average, the vein graft carries as much as 110 ml/minute of blood supply to the anterior circulation.52 Disadvantages of this method include donor–recipient size discrepancy, anastomotic distortion, inappropriate graft route, graft occlusion, cerebral hyperperfusion, and surgical manipulation during harvest and preparation of the vein segment.5,12,41,48,52 Okada, et al., reported the application of a subcutaneous Dacron tube to reduce the incidence of complications such as twisting and compression of vein grafts within the subcutaneous tunnel. The cervical-to-petrous ICA–saphenous vein in situ bypass technique, in which the cervical ICA is used as a tunnel for a vein graft, has also been reported to compensate for the disadvantages of saphenous vein bypass grafting.6 The RA is another option for an interposition graft in high-flow EC–IC bypass surgery.23,35,42 There are several theoretical reasons for using RA grafts. The caliber of the lumen in this graft more closely approximates that of small recipient vessels, such as the M₂ segment of the MCA. Also the RA has a uniform intimal wall that lacks valves. Nevertheless, blood flow through the RA graft is much less than that carried by a saphenous vein graft (approximately one half of that provided by a saphenous vein graft of a typical size).44 Consequently, the RA should be reserved for cases in which there is some collateral circulation.42,43

Rationale of Bypass Procedures. The ideal treatment of intracranial aneurysms should eliminate the aneurysm from the circulation and preserve blood flow through the parent vessel onto branch vessels. This treatment is best accomplished by direct clip placement across the aneurysm neck; however, aneurysms’ sizes, inaccessibility, lack of discrete necks, or other technical difficulties sometimes prevent clip placement. These aneurysms are sometimes unamenable to endovascular coil treatment. Alternative techniques for treating these unclippable aneurysms, including proximal vessel occlusion, trapping, or excision of the aneurysm, require neurosurgeons to establish cerebral revascularization to reduce the risk of ischemic disease.26–29,30 Furthermore, recent reports have revealed that an alternation or reduction in blood flow to the aneurysm by cerebral revascularization is an available option to reduce the risk of aneurysm growth and rupture without sacrificing vital vessels.7,10 This indicates that hemodynamics and direction of flow to aneurysms play critical roles in their rupture.

The involvement of the petrous or cervical ICA by a neoplasm represents a difficult surgical problem. In general, the most important principle for approaching neoplastic involvement of the ICA is the maintenance of cerebral circulation. This usually involves an attempt to dissect the ICA free from the neoplasm to preserve the artery. If a laceration of the ICA occurs during dissection, it is repaired or a venous patch graft is used. Only if the ICA is invaded by the tumor, cannot be dissected free from the tumor, or is damaged irreparably should consideration be given to ICA resection and/or cerebral revascularization by providing a high-flow bypass between petrous and suprachinoidal, cervical and petrous, or cervical and suprachinoidal segments of the ICA.23,33,44 These procedures require the exposure of the petrous ICA, which is generally considered to be a complicated and difficult procedure. Exposure of the entire petrous ICA was described by Fisch and colleagues16 with the sacrifice of conductive hearing function and transposition of the facial nerve. Glasscock, et al.,18 used a similar approach, but one involving temporary division of the facial nerve to treat a petrous ICA aneurysm. Selkar and associates46 used a preauricular infratemporal fossa approach for exposure of the cervical and petrous ICA. If exposure of the entire petrous ICA is not necessary, however, a portion of the horizontal segment of the petrous ICA can be exposed more easily for cerebral revascularization.

For treatment of patients with certain ischemic diseases, cerebral revascularization procedures still play an important role. Since the discouraging results of the International Cooperative Study of Extracranial–Intracranial Arterial Anastomosis,15 bypass surgery is rarely performed for the treatment of arteriosclerotic cerebral ischemic disease. Nevertheless, one limitation of the EC–IC bypass trial was that there was no method available at the time of the trial to assess the status of cerebral hemodynamics in the distal cerebral circulation.2,3,10 Recent reports advocate the use of positron emission tomography or single-photon emission computerized tomography scanning to predict the risk of stroke.11,22 Derdeyn, et al.,11 reported that an EC–IC bypass will be cost effective in patients with symptomatic CA disease in whom the oxygen extraction fraction is increased. It is important to evaluate the status of cerebral hemodynamics before bypass surgery. Current indications for bypass procedures in patients with symptomatic cerebral ischemia include the following: patients are unresponsive to optimal medical treatment; responsible lesions such as stenosis of the carotid siphon, are inaccessible for direct surgery; and a region of reduced perfusion has been documented either by direct measurement of regional cerebral blood flow or by metabolic studies. In addition, bypass surgery plays an im-
important role in the treatment of specific ischemic diseases, such as moyamoya disease and traumatic ICA injury.\textsuperscript{20,25,55} Moyamoya disease is characterized by spontaneous occlusion of the circle of Willis, which causes cerebral ischemia and/or intracranial hemorrhage. To prevent an additional ischemic attack and to reduce hemodynamic stress on the so-called moyamoya vessels, which tend to rupture leading to intracerebral hemorrhage, cerebral revascularization including STA–MCA anastomosis is performed. On the other hand, traumatic ICA dissections are likely to occur in younger patients. First-line therapy for traumatic ICA dissections routinely consists of anticoagulation therapy; however, traumatic ICA dissections tend to cause significant neurological deficits and require surgical intervention.\textsuperscript{33,34,40} Vishteh, et al.\textsuperscript{5} reported excellent outcomes after cerebral revascularization procedures had been performed for the treatment of patients with persistently symptomatic traumatic ICA dissections.

Cerebral revascularization techniques have been developed in the last three to four decades. The field is still developing with changes in technique and new indications for operative intervention such as a combination with endovascular procedures. The value of cerebral revascularization surgery as an aid to improve cerebral ischemia differs not only between neurosurgeon and physician, but also among neurosurgeons. It is important to understand the mechanism of each bypass procedure. Careful consideration, including the hemodynamic status of patients and difficulties with techniques, should be taken when a cerebral revascularization procedure is planned.

Acknowledgments

We thank Ronald Smith, M.S., Director, and David Peace, M.S., Medical Illustrator, of the Microneuroanatomy Laboratory, Department of Neurological Surgery, University of Florida, for constant support. We also thank Becky Norquist for reviewing the manuscript.

References

27. Kattner KA, Bailes J, Fukushima T: Direct surgical management of large bulbous and giant aneurysms involving the paraclinoid...
Cerebral revascularization: anterior circulation


