Experimental cerebral revascularization
with autogenous grafts

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Autogenous saphenous arterial or venous grafts were anastomosed between the
common carotid and the middle cerebral artery in 14 dogs with the aid of
microsuturing techniques and a new type of microtourniquet. Four of the six
saphenous artery grafts were patent when studied angiographically 4 to 70 days
postoperatively. Three of the eight venous grafts were patent when studied 1, 3,
and 18 days following surgery. The patency rate with arterial grafts was better
than that with venous grafts because of the ease of handling due to the thicker
wall, the reduced tendency toward redundancy and kinking, and the better
graft-to-host-artery ratio. Obvious technical factors were found that accounted
for all graft failures. Faulty suture placement; failure to remove an elliptical
segment of the host artery; twisting, angulation and kinking of vein grafts;
intimal flaps or adventitia caught in the suture line; and cerebral laceration and
subsequent infarction were all causes of failure. Successful cerebral revasculari-
zerion occurred only when these technical factors were surmounted and a sat-
isfactory graft-to-host-artery ratio obtained.

Key Words · cerebral revascularization · blood vessel prosthesis · autogenous venous and arterial grafts · microsuturing

"The vessels were handled very gently
and the endothelium was protected from
drying. No dangerous metallic forceps
were used. Great care was exercised to
obtain an accurate and smooth approxima-
tion of the endothelium of the vessels.
Stenosis or occlusion only occurs as a re-
sult of faulty technique."

Alexis Carrel, 1907

W ith the development of microsutur-
ing techniques, cerebral revascular-
zation with extra- to intracranial
shunts has become a reality. Two different
approaches have been attempted clinically,
the most frequently used being the superfi-
cial temporal artery to cortical artery anasto-
mosis. One of the authors (R.M.P.D.) has
personally performed this operation on nine
patients, and 40 additional cases have been
reported. The second approach is that
described by Woringer and Kunlin and
Lougheed, et al., who have used autoge-
 nous veins as bypass grafts between the com-
mon carotid and the intracranial internal ca-
rotid artery.

Both of these shunting procedures have
serious limitations. Due to the small size of
the superficial temporal and cortical arteries.
the supplementary blood flow provided may
not be sufficient to perfuse a markedly com-
promised cerebral circulation. Problems en-
countered with the autogenous vein graft
procedure include the technical difficulties
associated with procuring and using a long
vein graft and also the necessity of occluding
the internal carotid while suturing.

Previous laboratory attempts to obtain
long-term patency in autogenous grafts used
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for cerebral revascularization in the dog have been unsuccessful. This may have been secondary to the technical problems related to temporary vascular occlusion and also to excessive cerebral retraction. With the construction of a new microtourniquet for atraumatic temporary vascular occlusion and through a unique approach to the dog's middle cerebral artery, we have developed an experimental model that permits mobilization of a significant length of the middle cerebral artery without undue brain retraction or resection.

Using this model, we undertook to determine if successful revascularization of the dog's brain with autogenous arterial and/or venous grafts was indeed possible, and further, to delineate the technical factors that might be responsible for early graft failure.

Materials and Methods

Fourteen mongrel dogs weighing between 10 and 24 kg were anesthetized with pentobarbital sodium (25 mg/kg). Tracheal intubation was performed and the animals were placed in the lateral position. In two separate series we evaluated the patency of the autogenous saphenous artery and autogenous saphenous vein grafts anastomosed between the common carotid and the middle cerebral artery.

Preparation of Grafts

The saphenous artery and vein were exposed for approximately 10 to 14 cm, beginning in the inguinal region and extending beyond the knee joint. The desired vessel was excised in a manner to avoid damage to its walls at any time. A transected rubber band was passed around the vessel and used for elevation and manipulation. All branches or tributaries were occluded close to their origin with bipolar coagulation under magnification.

The arterial grafts were excised and immediately flushed with a solution of heparinized saline (10 mg/50 cc) and 1% procaine through a blunted 26-gauge needle. They were then kept moist in the same solution until ready for use.

The venous graft required a more delicate technique. Immediately before removal, 8-0 marking sutures were placed proximally and distally in the hemisected anterior venous wall to mark the longitudinal position. A small polyethylene catheter was then gently inserted into the distal end, and the graft was irrigated with the heparinized saline and procaine solution to remove blood clots and also to check for leaks. The catheter was then threaded through the entire vein to serve as an internal stent and to prevent later twisting and rotation.

To avoid the marked retraction that occurs with transection, the vein was tied to the catheter with 6-0 sutures proximally and distally. The remaining venous wall was sectioned and the graft removed and placed in the heparinized saline and procaine solution.

Carotid Artery Exposure

The common, internal, and external carotid as well as lingual, ascending pharyngeal and occipital arteries were exposed and separated from the surrounding connective tissue. Using the operating microscope, the adventitia was sharply excised from the common carotid artery at the selected graft site which was usually approximately 1 cm below its bifurcation.

Exposure of Middle Cerebral Artery

A vertical skin incision was made approximately 2 cm anterior to the ear and extending from the midline to the inferior border of the ramus of the mandible. The zygomatic arch and mandibular ramus were removed and the temporalis muscle was partially excised to expose the temporobasal skull.

A craniectomy was then performed which measured 2 cm in the anteroposterior, and 2½ to 3 cm in the vertical dimensions. The inferior margin extended to within 2 to 3 mm of the orbital fissure and optic canal. Only with this inferior bone exposure could we in most cases expose the main trunk of the middle cerebral artery without undue brain retraction.

Using magnification, the dura was opened to expose the main trunk of the middle cerebral artery as it crossed over the pyriform lobe and divided into two or more branches. With slight retraction, the more proximal middle cerebral artery, which measured between 0.8 and 1.2 mm in diameter, was brought into view. Under 16 magnification, a 4 to 6 mm segment of the middle cerebral artery was freed from its arachnoidal cover-
ing, and a rubber dam was placed under the artery after small penetrating cortical branches had been occluded with bipolar coagulation. Microtourniquets were then placed proximally and distally for later temporary arterial occlusion.

Carotid-Saphenous Artery Anastomosis

All the previously prepared carotid vessels were then occluded with bulldog or Scoville clips. Under magnification, a 2 to 3 mm transverse incision was made at the previously selected site on the common carotid. This was trimmed as necessary to obtain a "teardrop"-shaped opening. The proximal end of the saphenous artery measuring 1 to 1.3 mm in diameter was then split longitudinally and trimmed to fit against the incised common carotid artery. The graft was secured proximally and distally with 8-0 monofilament nylon suture, and the anastomosis completed with 12 to 16 interrupted sutures under 10 power magnification.

Carotid-Saphenous Artery Anastomosis

Because of the considerable difficulty in removing valves from the small veins, we sutured the smaller distal end of the vein to the common carotid and the larger proximal end to the middle cerebral artery. Initially, the same technique as that used for arteries was used for the vein grafts. It soon became apparent, however, that an internal stent was needed for support to prevent collapse of the very delicate vein wall and constriction at the suture line.

After taking great care to avoid rotation, we incised and prepared the carotid artery and saphenous vein as described above for the saphenous artery, and inserted the indwelling venous catheter into the common carotid artery. Eight zero (8-0) monofilament nylon interrupted sutures were again used to complete the anastomosis over the internal stent.

Graft to Middle Cerebral Artery Anastomosis

The distal end of the saphenous artery or proximal end of the saphenous vein was passed through the subcutaneous tissue with artery forceps into the prepared site of anastomosis to the middle cerebral artery. After removing the excess graft length as well as the venous internal stent, the graft opening was trimmed and stripped of adventitia for a few millimeters.

The middle cerebral artery was then occluded between the two microtourniquets, and an elliptical segment excised. This usually extended 1 to 1.5 mm along the middle cerebral artery for arterial grafts and 2 to 3 mm for the venous graft. The occluded segment of the middle cerebral artery was then irrigated with a heparinized saline solution.

Under 16 to 25 magnification, the anastomosis was completed with 10-0 monofilament nylon. Six to eight sutures were required for arterial grafts and 8 to 10 for the venous grafts.

The distal middle cerebral artery tourniquet was released first, and occasionally gelfoam was used to control oozing from the anastomotic site. The clamp on the external carotid was next removed followed by the proximal tourniquet on the middle cerebral artery and then the clamp on the common carotid. Finally, the internal and external carotid arteries were ligated so that all carotid blood flow entered the graft (Fig. 1).

All wounds were irrigated with sulfanilamide and sulfathiazole solution and closed in layers. Penicillin (400,0000 units) was given intramuscularly pre- and postoperatively. Systemic heparinization was not used.

Arteriography

Arteriography was performed at various
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intervals following surgery with Conray-60 (2 to 4 cc) injected through a polyethylene catheter inserted into the common carotid artery. Occasionally, a catheter was threaded directly into the venous or arterial graft. Immediately before injection, the common carotid was occluded proximally with a bulldog clamp to prevent reflux.

**Results**

A saphenous artery bypass procedure was performed in six dogs and a saphenous vein bypass in eight. Four of the six saphenous artery grafts were patent when studied angiographically 4 to 70 days postoperatively (Fig. 2). Three of the eight venous grafts were patent when studied 1, 3, and 18 days following surgery (Fig. 3). Results are summarized in Table 1.

The principles of microvascular suturing techniques outlined by others had to be followed meticulously to obtain patent grafts. Obvious technical errors were found that could account for all graft failures. In the saphenous artery series, Dog 1 had a markedly narrowed middle cerebral artery at the site of anastomosis due to faulty suture placement. Also, failure to remove an elliptical portion of the middle cerebral wall may have contributed to the failure. In Dog 4, thrombosis was probably related to a cerebral laceration and subsequent infarction due to excessive brain retraction.

The use of thin, non-ridged, and collapsible vein grafts greatly increased the technical problems which undoubtedly accounted for the poor results. All of the following factors singly or in combination contributed to thrombosis: twisting, angulation, redundancy, and kinking; luminal constriction at the common carotid-graft anastomosis; a carotid intimal flap occluding the vein ostium; the two-to-three-times larger size of the vein lumen compared to the middle cerebral artery; cerebral infarction secondary to retraction with subsequent poor "runoff"; gossamer-thin adventitia caught in the suture line; and in Dog 5 excessive manipulation during an attempt to obtain blood flow studies 18 days following the initial surgery.

An internal stent was used to overcome the problems of rotation, kinking, and nar-
TABLE 1

Summary of the autogenous graft experiments

<table>
<thead>
<tr>
<th>Dog Experiment No.</th>
<th>Days Followed</th>
<th>Result</th>
<th>Comment</th>
</tr>
</thead>
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<tr>
<td><strong>Saphenous Artery Grafts</strong></td>
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<td></td>
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</tr>
<tr>
<td>1</td>
<td>1543</td>
<td>7</td>
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<td>1584</td>
<td>9</td>
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</tr>
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<td>5</td>
<td>1562</td>
<td>35</td>
<td>patent</td>
</tr>
<tr>
<td>6</td>
<td>1616</td>
<td>14</td>
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</tr>
<tr>
<td><strong>Saphenous Vein Grafts</strong></td>
<td></td>
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<td></td>
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<tr>
<td>1</td>
<td>1636</td>
<td>1</td>
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</tr>
<tr>
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<td>1562</td>
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<td>patent</td>
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<td>3</td>
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<tr>
<td>5</td>
<td>1644</td>
<td>27</td>
<td>patent at 18 days, occluded at 27 days</td>
</tr>
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</tr>
</tbody>
</table>

Discussion

Yaşargil in this laboratory first attempted to interpose an autogenous saphenous artery graft between the common carotid and the middle cerebral artery in the dog. In the three animals used, all grafts were thrombosed when studied 4 to 8 weeks later. Failure was attributed to possible insufficient revascularization of the vaso vasorum in the transplanted arteries.

Experimental and more recent clinical data, however, indicate that long autogenous grafts do survive as a living tissue. In a study of the vascularization of vein grafts, Wyatt, et al., found that the nutrition of grafts is initially maintained by the plasmatic circulation. By 72 hours a capillary circulation is re-established similar to that seen in skin grafts. Dale, in a long-term study, evaluated narrowings of the proximal anastomosis. However, intimal trauma during stent insertion may have contributed to subsequent thrombosis since the catheter did not always pass easily.

Histology

The microscopic appearance of representative histological sections from the venous and arterial autografts did not differ from those experimental studies previously reported by numerous other investigators. Briefly, both types of grafts survive as living structures with preservation of the intima. Fibrous reinforcement of the venous and, to a lesser extent, the arterial autografts may occur, but this was not observed in this study, possibly due to the relatively brief time period involved.
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dog autogenous saphenous vein grafts of the same diameter and length as that used in our present study as femoro-femoral bypasses. He found that such grafts survived as a viable transplant although modified by some fibrosis when examined up to 790 days after surgery.

We have found, as have others, that it is the technical factors that are primarily responsible for early graft failure. The elegant studies and observations of Alexis Carrel over 60 years ago on the surgery of large blood vessels are just as appropriate today in microvascular surgery. Gentleness, smooth approximation of the vessels, and protection from drying are essential. Because of the ease of handling, results with saphenous artery grafts were predictably better than those using saphenous veins. In this study a technique that permitted patency in a saphenous artery graft required further polish to obtain even short term patency in a vein graft.

Presumably, results with larger vessels and with the improved exposure that could be obtained clinically might be better than those reported here. Important factors that must be considered before clinical application, however, include: 1) a selection of a suitable graft that can be readily prepared; 2) the selection of a host artery of appropriate dimensions and accessibility; and 3) the need to avoid prolonged interruption of the cerebral circulation during suturing.

Concerning graft selection, a synthetic material of proper dimensions would be ideal. Unfortunately, all attempts to maintain patency through prosthetic grafts of less than 4 mm in diameter have failed. We are presently evaluating a new thrombo-resistant Hydro-gel® which has an intraluminal electronegative surface effect, but efforts thus far are still preliminary. Homologous arteries used for small vessel replacement have also been unsatisfactory due to local host tissue response and progressive degeneration and fibrosis. Since autogenous arteries of the proper dimensions cannot be safely used for fear of local ischemia, autogenous veins presently appear to be the best available graft material.

Indeed, autogenous saphenous veins have been used as bypass grafts in the only two reported clinical cases of common carotid to internal carotid shunts. Technical problems similar to those we experienced were encountered in both patients. To avoid valve obstruction Woringer and Kunlin reversed the vein graft, but then had a 5 mm lumen which they joined end-to-end to a 3 mm internal carotid. They sutured the vein graft obliquely, and it remained patent until the patient's death from a pulmonary embolus the evening following surgery. At autopsy, although patent, a small clot was observed on the suture line.

Lougheed, et al., on the other hand, inverted the graft, removed the valves, and then re-inverted the vein. A branch near the small (distal) end was then sutured to the internal carotid in an end-to-end fashion. This graft remained patent for approximately 7 months when it suddenly occluded for unexplained reasons.

The tediousness of vein graft preparation significantly contributed to the prolonged operating time of 12 and 17 hours in the respective clinical cases as well as in the present laboratory study. It would appear, however, that angulation, kinking, and narrowing of the vein lumen due to collapse was less of a clinical problem than we experienced. Regardless, provided that the technical problems associated with vein grafts as outlined above can be overcome, a separate surgical team to obtain and remove the graft would seem advisable.

In addition to the underlying disease process, the second major clinical consideration, that of selection of a host intracranial artery, is dependent on the accessibility, the absence of essential branches in the area to be sutured, and the arterial size in relation to the graft. Szilagyi, et al., recommended that a ratio of 1:1.4 to 1:1.6 between the proximal host artery and the graft be obtained since any increase in the diameter of the graft over the recipient artery will reduce the flow velocity, promote turbulence, and increase the danger of thrombosis. In our arterial graft series, the ratio never exceeded 1:1.5, but in the vein grafts series it was in the range of 1:2.5 or more, which, all other factors considered, may have further contributed to the poor results.

In extrapolating to the possible clinical
situation, we find that the lumen of the proximal saphenous vein in man varies between 3 and 6 mm in diameter. The primary accessible intracranial vessels large enough to accept such a graft are the internal carotid, which in the fixed state usually ranges between 2.5 and 3.6 mm and the middle cerebral artery which is between 2 and 2.5 mm.1,7

In cadavers we have found that a saphenous vein graft, or a branch thereof as used by Lougheed, can be sutured to either of these vessels while maintaining a satisfactory artery-to-graft ratio. Furthermore, by using microtourniquets, this could be done between a segment freed of arachnoid for only 7 to 9 mm. If standard vascular clips were used for temporary occlusion, an additional 3 to 5 mm arterial segment was needed to obtain an adequate and unobstructed working distance between the clips.

Perhaps the most critical problem to be avoided, however, in any extra-intracranial shunting procedure is that of prolonged interruption of the blood supply during the period of anastomosis. One way to maintain flow and to avoid this problem is to use an internal bypass which may be removed immediately prior to completing the suture line.

We have extensively evaluated intraluminal stents of silicone rubber in vessels of 1 to 3 mm in diameter in laboratory animals and have found that end-to-end as well as end-to-side anastomosis can be readily performed with minimal interruption of the blood supply. Special care must be taken, however, to be most gentle and to use a stent of correct size; otherwise, intimal trauma may lead to thrombosis.4 Such bypasses were not used in the present study because we could not obtain satisfactory proximal control of the middle cerebral artery to insert a stent without excessive brain retraction or interruption of the lenticulo-striate branches. Furthermore, we found that neurological deficits rarely occur in the dog when the middle cerebral artery is occluded distal to the lenticulo-striate arteries and proximal to its bifurcation or trifurcation. From our laboratory and cadaver experience, however, it would seem that intraluminal stents could be used to maintain cerebral blood flow while performing intracranial anastomoses.

Despite the many problems associated with cerebral revascularization with autogenous grafts, the previous clinical attempts and our present laboratory experience suggest that it is indeed a feasible possibility. Long-term laboratory studies of various graft materials, the possible histological changes which may occur, as well as cerebral and graft blood flow determinations are definitely needed and may be provided by the experimental model we have described. From the results of others who have used autogenous grafts and microsuture techniques, it would seem that such grafts do have a reasonable chance for prolonged patency.

As pointed out by Yasargil, it now depends on the development of methods for evaluating cerebral blood flow and metabolism so that objective indications for operations may be better defined.

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