Geometric dimension changes with carotid endarterectomy reconstruction

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Purpose: The geometry of carotid endarterectomy (CEA) reconstruction is a major determinant of carotid bifurcation hemodynamics that, in turn, may play a significant role in the likelihood of early postoperative thrombosis and early and late restenosis. The purpose of this study was to measure the geometry of various types of CEA reconstructions.

Methods: Six carotid artery diameters and lengths were measured during surgery, before and after CEA. Three reconstruction methods were used in 562 CEA procedures: a greater saphenous vein patch in 389, a synthetic patch in 157, and primary closure in 16. Veins 6 mm or more in distended diameter were trimmed before use as a patch. Synthetic patches were 8 to 11 mm in width. Patch reconstruction was used when the length of the arteriotomy required to obtain a complete distal endarterectomy end point extended beyond the internal carotid artery bulb. Saphenous vein patches were used when it was available and adequate. Neither gender nor internal carotid artery diameter was used as a criteria for the selection of the reconstruction method.

Results: Before endarterectomy, the 302 male carotid arteries had 7% to 15% greater linear dimensions than the 260 female arteries ($p < 0.001$). Both vein and synthetic patch reconstruction produced up to 16% changes in linear dimensions except for almost doubling of the length of the internal carotid bulb. Patching made the elliptical common carotid bulb significantly more round, but the maximum diameter of curvature of the carotid bulb remained unchanged. Primary closure slightly decreased the diameter of the internal carotid bulb.

Conclusions: CEA patch reconstruction has two major effects on carotid geometry: an increase in internal carotid bulb length and a more round common carotid bulb. The former allows for a gradual transition from the terminal common carotid bulb to the uniform diameter more distal internal carotid artery. It also separates the two major causes of disturbed flow: the bifurcation and the step-down in internal carotid artery diameter. Primary closure has minimal effect on preoperative geometry. (J Vasc Surg 1997;25:488-98.)

Carotid endarterectomy (CEA) patch reconstruction has a low incidence of early postoperative internal carotid artery thrombosis and early and late restenosis.[1-6] Patch reconstruction has been reported to be most beneficial in women and in patients with small internal carotid arteries.[2-4] The reasons for this are unclear and probably multifactorial. One possibility is altered carotid bulb geometry. Local hemodynamics play a role in arterial thrombosis,[7,8] atherogenesis,[9,10] myointimal hyperplasia,[11] and restenosis.[12] High and low wall shear stresses, wall shear stress gradients, flow separation, and flow stagnation with prolonged transit times that increase the potential for particle deposition and transport are associated with focal areas of atherosclerotic plaque and myointimal development.[9,10,13-15] The hemodynamically ideal CEA reconstruction has minimal pulsatile flow disturbances. Two of the major sources of localized flow disturbances in the extracranial carotid arteries are at the bifurcation and the diameter step-down from the internal carotid bulb to the distal internal carotid artery. Patch reconstruction may modify these. In addition, patch reconstruction of CEA may result in an enlarged carotid bulb, making patch rupture, intraluminal thrombus, and aneurysm formation more likely. However, there is little information on the geometric changes produced by various types of CEA reconstructions.[5,16] This is a report of the changes in geometry of the carotid artery with CEA

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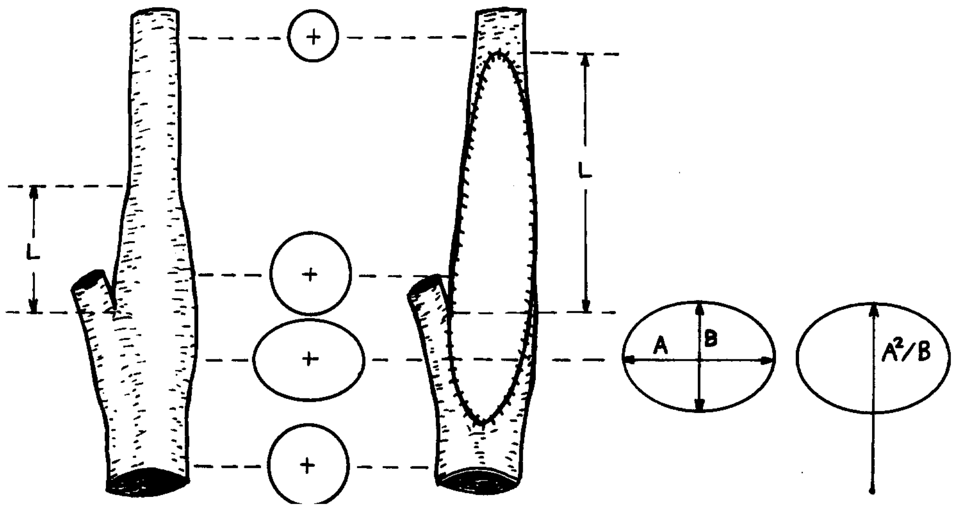

Fig. 1. Carotid artery schematic illustrating the six linear dimensions measured before carotid endarectomy (CEA; *left*) and after patch reconstruction *(right)*. The major and minor diameters (*A* and *B*) of the elliptical common carotid bulb were measured as shown on the far right and the maximum diameter of curvature, A^2/B, calculated.

reconstruction by use of greater saphenous vein patches, synthetic patches, and primary closure.

METHODS

Patients and operations. Of 591 primary CEA procedures performed between 1989 and mid-1995, 562 had complete intraoperative geometric measurements before and after CEA and are the basis of this report. Although similar geometric measurements were made on approximately 500 CEA reconstructions between 1983 and 1989, many did not have complete measurements before CEA sufficient to calculate the elliptical common carotid bulb geometry and are therefore not included in this study. There were 302 male and 260 female carotid arteries. The indications for CEA were transient ischemia or amaurosis fugax in 205 patients (37%), reversible ischemic neurologic deficit in 19 (3%), stroke in 67 (12%), nonlateralizing transient ischemia in 51 (9%), and asymptomatic >75% diameter stenosis in 220 (39%). The method of CEA has been reported.[17] The reconstruction method used—patch or primary closure—was determined by the length of the arteriotomy required to obtain a complete endarterectomy end point in the internal carotid artery. A patch was used if the arteriotomy extended distal to the bulb segment of the internal carotid artery.[17] Neither the preoperative geometry, including the diameter of the internal carotid artery, nor gender played a role in the decision to patch. A greater saphenous vein patch was most frequently used in the first 4 years of this series if it was available and had a distended diameter of 3.5 mm or more.[18] A Dacron patch was more frequently used in the past 18 months. There were 389 saphenous vein patches (69% of all; 71% of patches). There were 157 synthetic patches (28% overall; 29% patches). Of the 146 Dacron patches, the last 96 were the recently available precut 8 mm wide patches (Hemashield, Meadox Medicals Inc., Oakland N.J.). The other 50 Dacron and 11 polytetrafluoroethylene (PTFE) patches were cut to 8 to 11 mm wide from larger pieces. Saphenous veins 6 mm or more in distended diameter were trimmed before use as a patch. Primary closure was used in the 16 CEA reconstructions (3% of all) in which a complete distal endarterectomy could be done without extending the arteriotomy incision beyond the internal carotid bulb. Eversion plication shortening of the endarterectomized segment of the internal carotid artery to prevent kinking[17] was performed in 61 (11%) CEA reconstructions. All 61 of these CEA had patch reconstruction. Carotid duplex scans were done at least once in the first postoperative year in 527 (94%) of the arteries (Ultra Mark 8 or Ultra Mark 9; Advanced Technology Laboratories, Bothell, Wash.).

Measurements and calculations. After exposure and before occlusion, six linear dimensions were measured to the nearest ½ mm with a caliper, as illustrated in Fig. 1. After reconstruction and reestablishment of blood flow, the six measurements were repeated. The internal carotid bulb diameter was

Table I. Geometric dimensions for 302 male and 260 female carotid arteries measured intraoperatively before endarterectomy

	Male	*Female*	*% Difference*	*All*
Internal carotid diameter distal to bulb (mm)	5.27 ± 0.69**	4.89 ± 0.60	7.6	5.10 ± 0.68
Internal carotid bulb diameter (mm)	8.23 ± 1.22**	7.37 ± 1.03	11.0	7.63 ± 1.21
Internal carotid bulb length (mm)	13.2 ± 3.3**	11.4 ± 3.0	14.6	12.4 ± 3.2
Common carotid bulb major diameter (mm)	12.5 ± 1.52**	11.0 ± 1.23	12.4	11.8 ± 1.57
Common carotid bulb minor diameter (mm)	10.3 ± 1.24**	9.28 ± 1.00	10.9	9.85 ± 1.25
Common carotid bulb maximum diameter of curvature (mm)	15.4 ± 2.6**	13.3 ± 2.1	14.6	14.4 ± 2.6
Common carotid bulb eccentricity (dimensionless)	0.550 ± 0.104*	0.526 ± 0.112	4.5	0.539 ± 0.109
Common carotid bulb circumference (mm)	36.1 ± 4.10**	32.0 ± 3.32	12.0	34.2 ± 4.25
Common carotid diameter proximal to bulb (mm)	8.70 ± 0.87**	8.07 ± 0.77	7.6	8.41 ± 0.88

All values are mean ± 1 SD.
*$p < 0.05$; **$p < 0.001$ by unpaired *t* test.

measured 3 to 4 mm distal to the bifurcation. Because the common carotid bulb is elliptical in cross-section, the major and minor axis diameters—A and B, respectively—were measured 4 to 5 mm proximal to the bifurcation. The location of the maximum diameter of curvature of an ellipse is at the intersection of the minor diameter of curvature, B, as shown in Fig. 1. The maximum diameter of curvature of an ellipse is A^2/B, the circumference is $\Pi[(A^2 + B^2)/2]^{1/2}$, and the eccentricity is $(A^2 - B^2)^{1/2}/A$. The eccentricity of a circle is zero. All data was prospectively stored in a computer registry. Statistical analysis was by paired and unpaired *t* testing with the Bonferroni correction for multiple comparisons and ANOVA (JMP Statistical Software, SAS Institute, Cary, N.C.). Numerical values are presented as mean ± 1 SD in tables and mean ± 2 SE in figures. Percentage difference between two measurements x and y were calculated as follows: $[2(x - y)/(x + y)]100$. Percentage change between two measurements x to y were calculated as follows: $[(y - x)/x]100$.

RESULTS

The measured and calculated dimensions before CEA are given in Table I for the 302 male and 260 female carotid arteries. Linear dimensions in men were 7% to 15% greater than those of women. The internal carotid artery diameter distal to the bulb after CEA was 5.07 ± 0.64 mm, 5.23 ± 0.67 mm for men and 4.88 ± 0.55 mm for women ($p < 0.001$). The common carotid artery diameter proximal to the bulb after CEA was 8.37 ± 0.85 mm: 8.65 ± 0.83 mm for men and 8.03 ± 0.75 mm for women ($p < 0.001$). These two diameters should not and did not change from before CEA values ($p = 0.7$ to 0.9 by paired *t* test) because they are proximal and distal to the arteriotomy and reconstruction.

The six measured and calculated dimensions before and after CEA for the types of CEA reconstructions are given in Figs. 2 to 7 for all male and female arteries, respectively. Patch reconstruction increased the internal carotid bulb diameter from 3% to 11% ($p < 0.01$ to $p < 0.001$; Fig. 2). The use of the precut 8 mm wide Dacron patch (DAC-2) increased this dimension less than earlier Dacron patches (DAC-1; $p < 0.001$). In general, patching increased the internal carotid bulb diameters more in women than in men. Primary closure significantly decreased the internal carotid bulb diameters ($p < 0.001$ by paired *t* test) but were within 10% of the preoperative values. As expected, patching increased the internal carotid bulb length from 76% to 92% ($p < 0.001$; Fig. 3). However, in the 61 CEA reconstructions with internal carotid bulb shortening, the increase in internal carotid bulb length was from 24% to 68% ($p < 0.001$). Patch reconstruction increased the common carotid major diameters up to 10% ($p < 0.01$; Fig. 4). Primary closure did not significantly change this dimension. However, the common carotid bulb maximum diameter of curvature remained essentially unchanged for all types of reconstructions ($p > 0.1$; Fig. 5). The explanation for this is the patch reconstruction groups is a more round bulb as reflected by the eccentricity, which decreased from 24% to 68% ($p < 0.01$; Fig. 6). The changes in the common carotid bulb maximum diameter of curvature and eccentricity were similar in men and women. Patching increased the common carotid bulb elliptical circumference from 3% to 8% in men and from 7% to 16% in women ($p < 0.05$; Fig. 7). This dimension was unchanged by primary closure.

In this series of 562 primary CEA reconstructions in 518 patients, there were four deaths (0.7% for operations; 0.8% for patients) in the 30-day perioperative period. Three were caused by myocardial in-

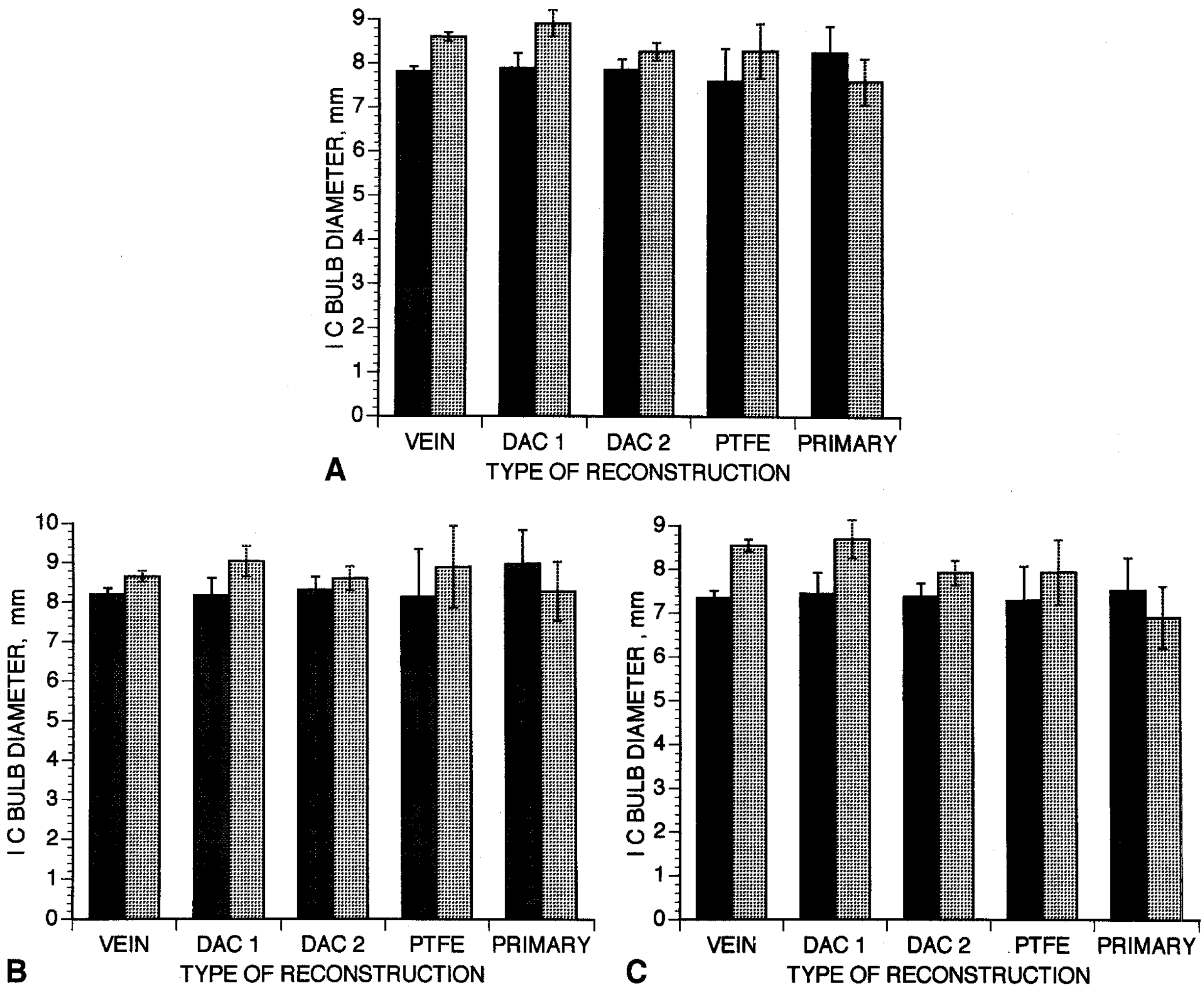

Fig. 2. Internal carotid *(IC)* bulb diameter before *(dark bars)* and after *(light bars)* CEA for all 562 arteries **(A)**, 302 male arteries **(B)**, and 260 female arteries **(C)** by type of reconstruction. Bars are mean ± 2 SE. There are 389 vein patches, 50 Dacron 1 (DAC-1) patches (cut from a larger piece), 96 Dacron 2 (DAC-2) patches (precut 8 mm), 11 polytetrafluoroethylene (PTFE) patches, and 16 primary closures. By unpaired *t* testing all vein ($p < 0.001$) and DAC-1 ($p < 0.01$) dimensions increased significantly with CEA, as did DAC-2 in women ($p < 0.01$). The other two synthetic patches did not produce a statistically significant increase. The decrease in diameter in the primary closure group was not statistically significant. By paired *t* testing the internal carotid bulb diameter increased in all patch reconstructions and decreased in primary closure ($p < 0.001$ for all except in DAC-2 which was $p < 0.05$).

farction on days 1, 3, and 15, respectively, the latter occurring after hospital discharge. Hyperperfusion syndrome developed in the other patient on day 7; the patient had an in ipsilateral cerebral hemorrhage on day 8 and subsequently died. There were six strokes (1.1% operations; 1.2% patients) within 30 days. One of these was in the patient with the severe hyperperfusion syndrome who died and the other five were relatively mild and resolved in 1 to 3 months. Of these five strokes, one was caused by the hyperperfusion syndrome, one was caused by an embolus from the common carotid artery step, two were contralateral to the CEA (one of cardiac origin in a patient who had combined coronary bypass and CEA and the other in a patient with a 90% contralateral carotid stenosis), and one in the cerebella distribution. The overall 30-day death and stroke rate was 1.8% for operations and 2.0% for patients. There were no patch ruptures.

Postoperative duplex scanning showed a ≥50%

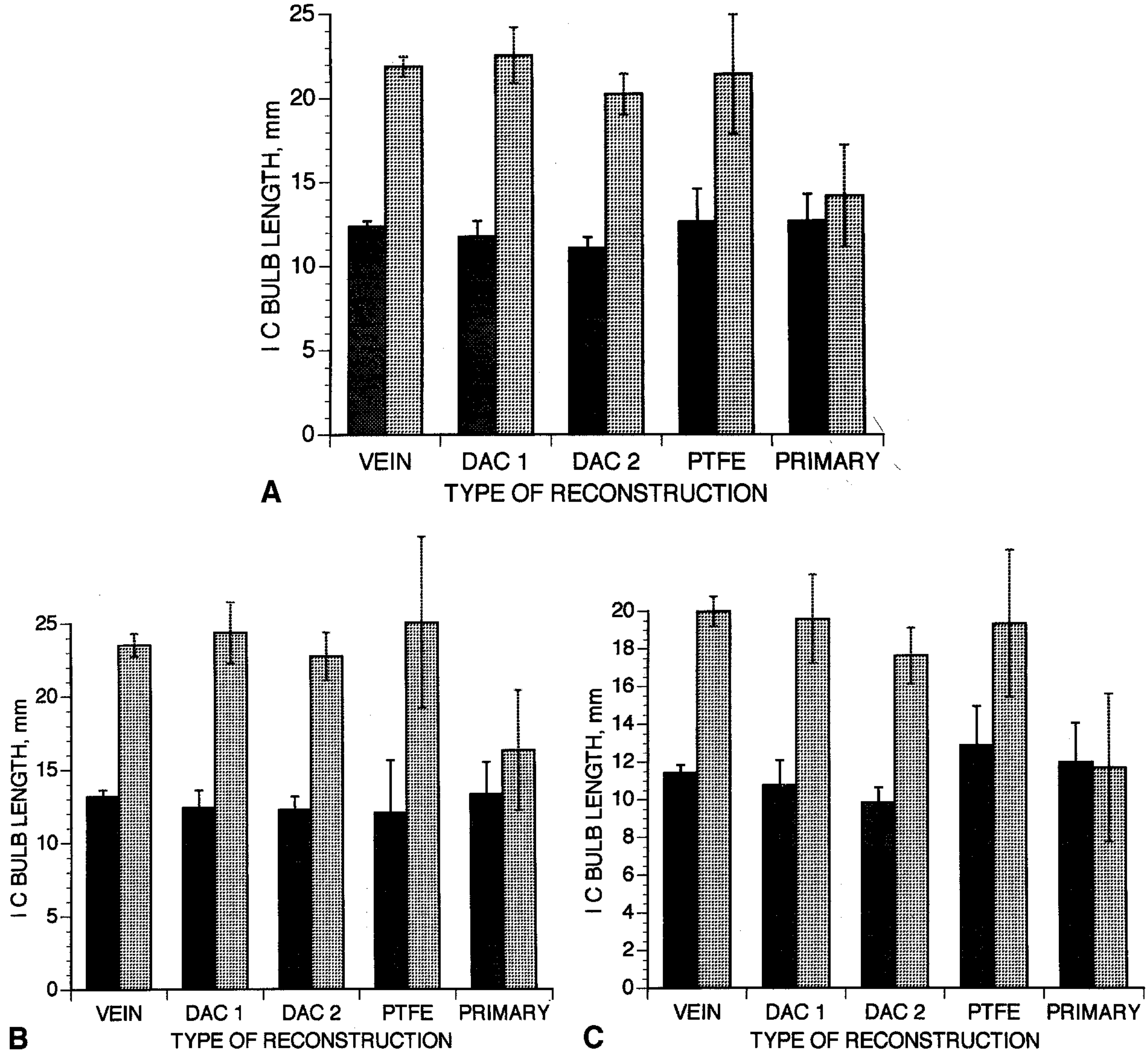

Fig. 3. IC before *(dark bars)* and after *(light bars)* CEA for all 562 arteries **(A)**, 302 male arteries **(B)**, and 260 female arteries **(C)** by type of reconstruction. Bars are mean ± 2 SE. There are 389 vein patches, 50 DAC-1 patches (cut from larger piece), 96 DAC-2 patches (precut 8 mm), 11 PTFE patches, and 16 primary closures. By both paired and unpaired *t* testing, all patch reconstructions increased this dimension ($p < 0.001$). The changes with primary closure were not significant by either method of testing.

diameter stenosis in five CEA reconstructions (0.95% of arteries studied). Two of these occurred in the saphenous vein patch group (0.5%). One of these was an asymptomatic internal carotid occlusion identified at 6 weeks in a patient in whom deep venous thrombosis developed on the ninth postoperative day in the leg from which an ankle vein was harvested. This is the only early internal carotid occlusion I have found in approximately 1000 primary CEA reconstructed with a greater saphenous vein patch. One additional patient with a vein patch had no recurrent stenosis for the first 3 years and then developed a >75% diameter stenosis in the region of the endarterectomy-produced common carotid step and underwent reoperation at 5 years. Two restenosis occurred in the synthetic patch group (1.3%), one DAC-1, one PTFE). One patient with primary closure (6%) was found to have a >75% stenosis at the location of the common carotid step at 6 months and underwent reoperation at 9 months when the stenosis progressed further. An additional three arteries reconstructed with a synthetic patch (two DAC, one

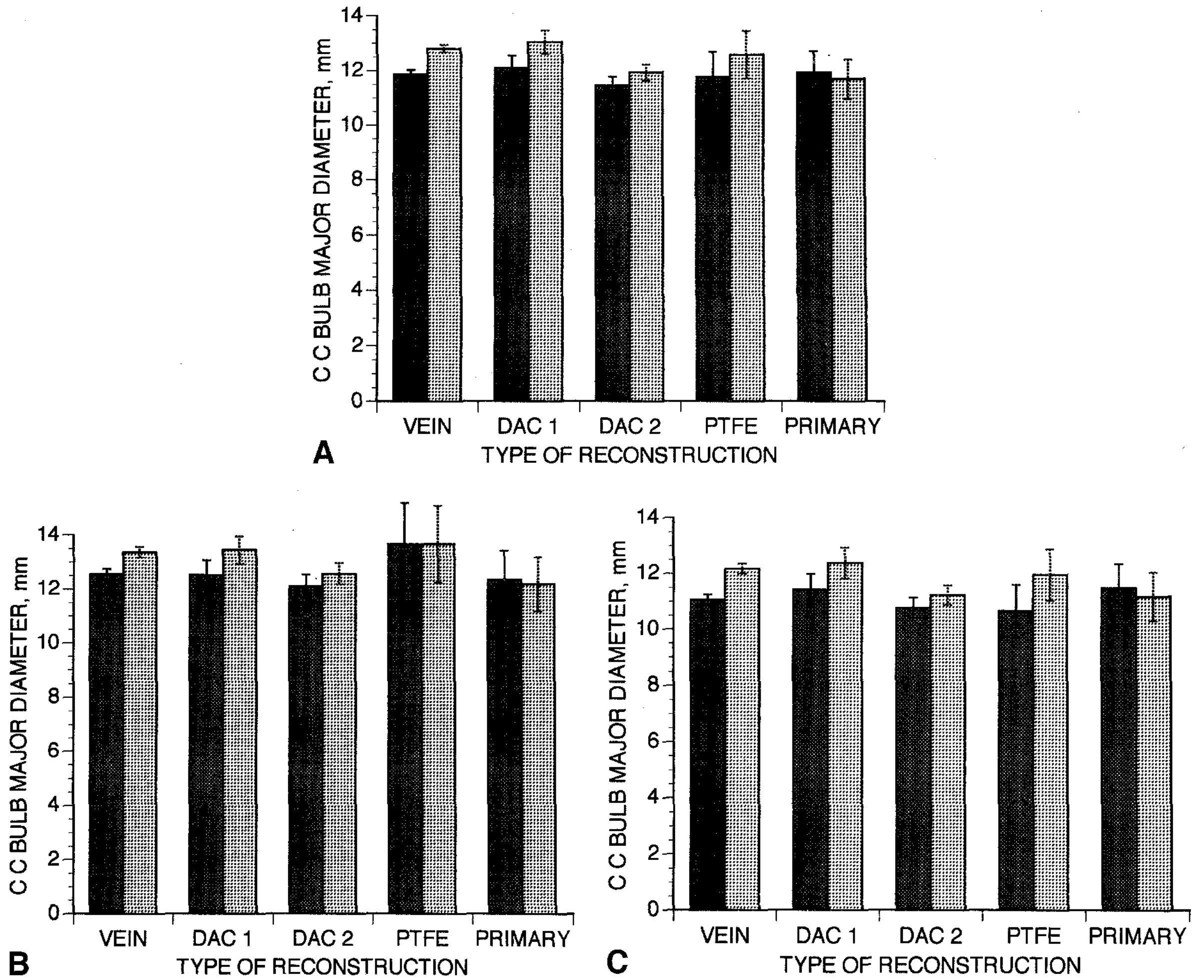

Fig. 4. Common carotid *(CC)* bulb major diameter before *(dark bars)* and after *(light bars)* CEA for all 562 arteries **(A)**, 302 male arteries **(B)**, and 260 female arteries **(C)** by type of reconstruction. Bars are mean ± 2 SE. There are 389 vein patches, 50 DAC-1 patches (cut from larger piece), 96 DAC-2 patches (precut 8 mm), 11 PTFE patches, and 16 primary closures. By unpaired *t* testing, only vein patching increased this dimension ($p < 0.01$). By paired *t* testing, all patch material increased this dimension ($p < 0.01$, except DAC-2, $p < 0.05$). There were no statistically changes in the primary closure group by either method of testing.

PTFE) had approximate 90-degree kinks in the internal carotid artery just distal to the patch. These occurred early in this series before a more aggressive approach was taken to prevent kinking by eversion plication shortening of the endarterectomized internal carotid segment. One patient with a vein patch was found by scanning to have a 1 cm diameter false aneurysm in the proximal suture line at 6 weeks. This was repaired with a single suture.

DISCUSSION

The data presented in this study are the result of a CEA technique that incorporates a complete internal carotid end point and a tapered, smooth, nonkinked reconstruction that produces minimal flow disturbances. Imparato[19,20] has emphasized that CEA patch reconstruction should be used not to increase the vessel diameters but rather to alter the preoperative geometry to minimize the abnormal response of the arterial wall to disturbed flow that can lead to thrombosis, myointimal proliferation, and atheroma. He also indicated that the quantitative effect of patching on geometry was unclear and that the optimal reconstruction geometry was unknown.[19,20] This study is an attempt to quantitatively define what patch reconstruction does to preoperative geometry, following the general guidelines set out by Imparato.[19,20]

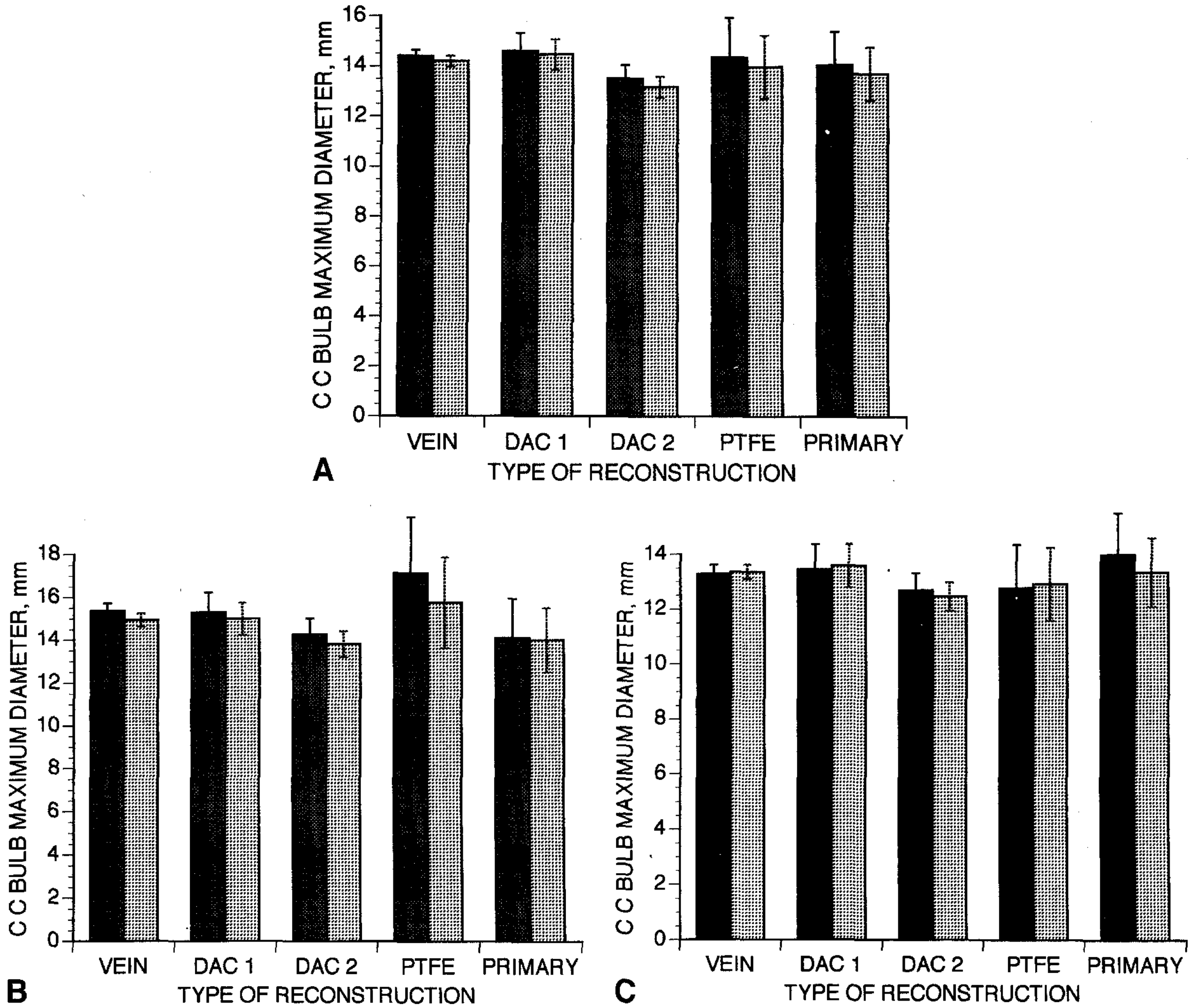

Fig. 5. CC bulb maximum diameter of curvature before *(dark bars)* and after *(light bars)* CEA diameter for all 562 arteries (**A**), 302 male arteries (**B**), and 260 female arteries (**C**) by type of reconstruction. Bars are mean ± 2 SE. There are 389 vein patches, 50 DAC-1 patches (cut from larger piece), 96 DAC-2 patches (precut 8 mm), 11 PTFE patches, and 16 primary closures. There were no statistically significant changes by either paired or unpaired *t* testing in any group or subgroup.

The results of this study are interesting and in several ways unexpected. The minimal effect of patching on the internal carotid bulb diameter is interesting and reflects my technique of gradually tapering the reduction in internal carotid bulb diameter, tailoring the patch and taking deep suture bites in the endarterectomized arterial wall. This may be important in keeping the diameters small and, in the case of vein patch reconstruction, maximizing the endothelial surface. The increase in length of the internal carotid bulb in the patched groups is expected because the arteriotomy extended distal to the bulb in these operations. The most significant findings are those in the common carotid bulb. The maximum diameter of curvature was unchanged by patch reconstruction. This means that vein patching does not increase the maximum circumferential or hoop wall stress, as we previously thought.[16,18] The highest circumferential wall stress occurs at the points of maximum diameter of curvature of the elliptical common carotid bulb. The two points are on the minor axis (*B* on Fig. 1) of the elliptical cross-section, which are the middle of the patch anteriorly and the posterior endarterectomized wall. This is where central vein patch rupture occurs.[21-24] When greater saphenous vein is used as a patch, the

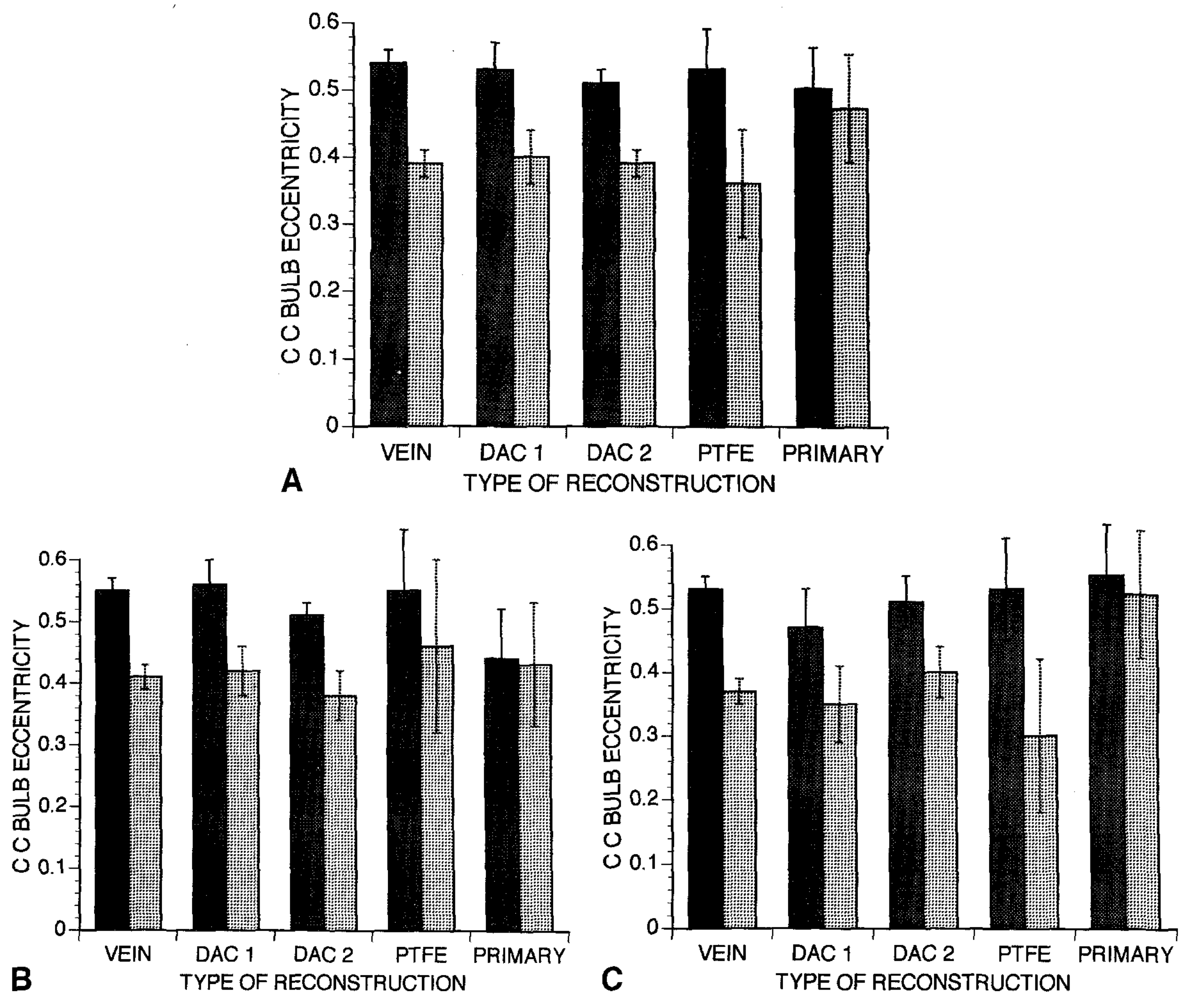

Fig. 6. CC bulb eccentricity before *(dark bars)* and after *(light bars)* CEA for all 562 arteries **(A)**, 302 male arteries **(B)**, and 260 female arteries **(C)** by type of reconstruction. Bars are mean ± 2 SE. There are 389 vein patches, 50 DAC-1 patches (cut from larger piece), 96 DAC-2 patches (precut 8 mm), 11 PTFE patches, and 16 primary closures. By both paired and unpaired *t* testing all patch groups and subgroups decreased this dimension ($p < 0.01$). There was no change produced by primary closure ($p < 0.05$) by either method.

vein's circumferential wall stress is increased as a result of an increase in diameter of curvature and transluminal pressure,[16,18] but there is no further increase in wall stress because of the three-dimensional geometric changes of the common carotid bulb. To put it another way, the maximum circumferential wall stress on a vein patch reconstruction is no greater than that produced in a carotid artery closed primarily to its dimensions before CEA. Patching makes the elliptical common carotid bulb significantly more round; that is, the elliptical eccentricity decreases. That is why the maximum diameter of curvature does not change. In a recent study of CEA vein patch rupture,[24] it was recommended that the maximum diameter of curvature of the common carotid bulb be kept less than 14 mm and that the major diameter (*A* on Fig. 1) be kept less than 13 mm. This is consistent with the qualitative recommendation of Imparato[19,20] and the reconstructive techniques used in this study. However, a number of the common carotid bulb diameters in this study exceeded these values. To decrease the bulb diameters and the magnitude of transition from the terminal common carotid to the uniform diameter internal carotid, further improvement in my reconstructive technique is needed.

In a previous report, we used intraoperative reconstruction geometric measurements after CEA to theoretically extrapolate the effect of patching on hemodynamics.[16] The current study was undertaken

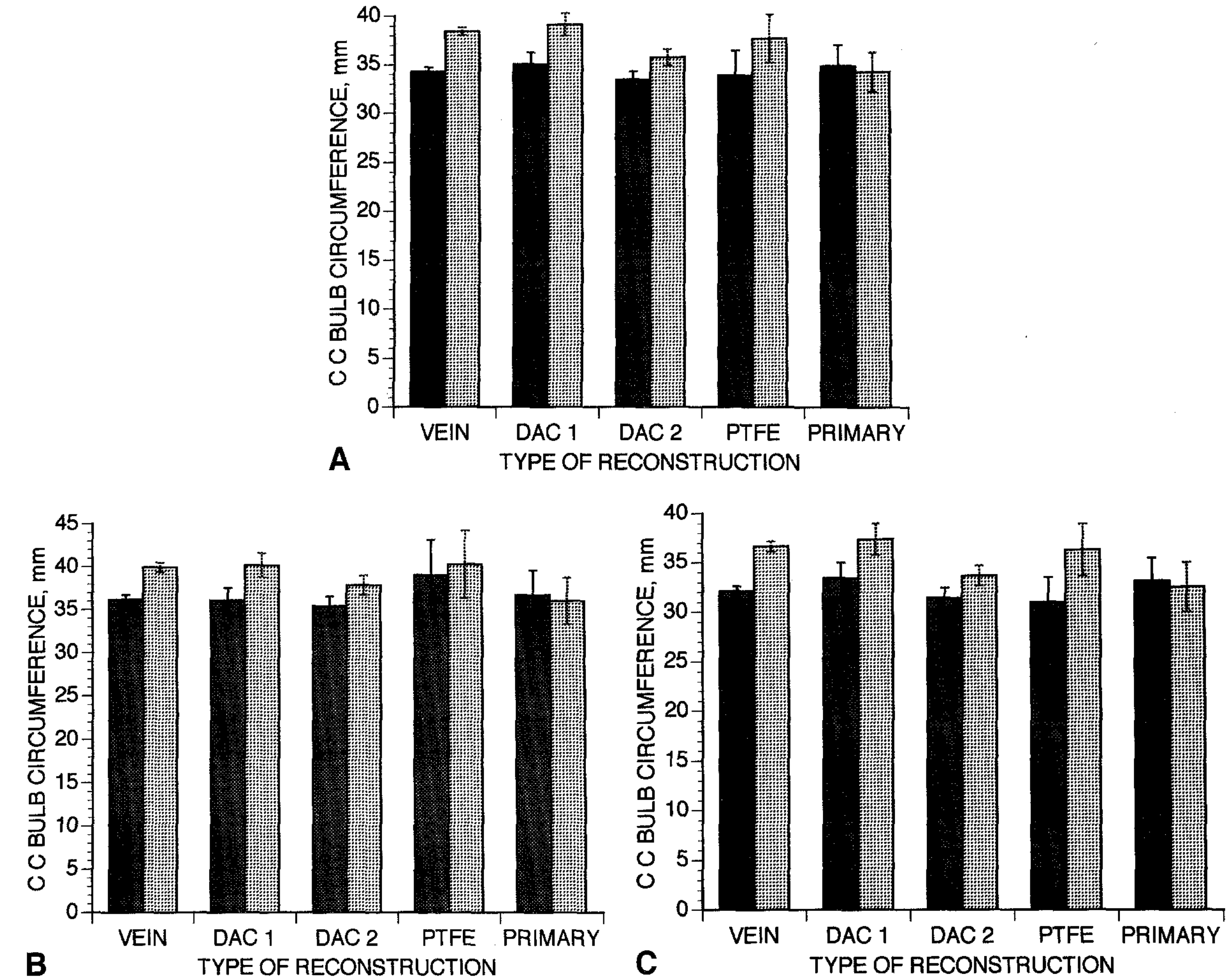

Fig. 7. CC bulb circumference before *(dark bars)* and after *(light bars)* CEA for all 562 arteries (**A**), 302 male arteries (**B**), and 260 female arteries (**C**) by type of reconstruction. Bars are mean ± 2 SE. There are 389 vein patches, 50 DAC-1 patches (cut from larger piece), 96 DAC-2 patches (precut 8 mm), 11 PTFE patches, and 16 primary closures. Patching increased this dimension ($p < 0.01$, unpaired *t* test; $p < 0.001$, unpaired *t* test), except for PTFE in women ($p < 0.05$). There was no statistically significant change produced by primary closure by either method of testing.

to determine how CEA reconstruction changes the three-dimensional carotid artery geometry relative to the preoperative state. Of particular interest are the geometric changes produced by patch reconstruction, as well as the final geometry. This information is also important because of qualitative observations and suggestions that patch reconstruction produces an enlarged carotid bulb that may be prone to thrombus formation,[7,12] patch rupture,[18,21-24] and aneurysm formation.[6] The results of this study do not support the enlargement theory. We prevented enlargement of the arteries by patching in this study by taking deep suture bites in the arterial wall, thus narrowing the diameter to compensate for the patch, excluding significant amounts of the endarterectomized surface, and hemodynamically tailoring the reconstruction.

The small number of primary closure reconstructions in this series do not allow for a valid comparison of clinical outcome with patch reconstruction, and that was not the purpose of this study. However, there is ample evidence to support the advantage of patching. There are five randomized clinical studies of patch versus primary closure CEA reconstruction.[3-6,25] Although results are variable between the five studies, and two of them excluded women with small internal carotid arteries,[3,5] the pooled incidence of early postoperative internal carotid thrombosis was 15 of 377 (4.0%) in the primary closure groups and three of 314 (0.9%) in the patched groups ($p = 0.007$ by two-tailed Fisher's exact test). Similarly, three pooled nonrandomized studies[1,2,26] reported the early postoperative internal carotid thrombosis rate to be 24 of 653 (3.7%) for primary closure and two of 584 (0.3%) for saphenous vein patch reconstruction ($p < 0.001$). The incidence of 30-day stroke in the five randomized studies[3-6,25] was 12 of 327 (3.7%) for primary closure and seven of 374 (1.9%) for patch reconstruction ($p = 0.09$). The three nonrandomized studies[1,2,26] had a pooled stroke rate of 18 of 630 (2.8%) for primary closure and three of 576 (0.05%) for patch reconstruction ($p = 0.0012$). The pooled rate of recurrent stenosis ≥50% within 1 year in the five randomized studies was 22 of 313 (7.0%) for primary closure and four of 397 (0.3%) for patch reconstruction ($p < 0.0001$). Similarly, four nonrandomized studies[1,2,26,27] have a pooled incidence of recurrent stenosis ≥50% in 1 year of 43 of 702 (6.1%) for primary closure and five of 626 (0.8%) for patch reconstruction ($p < 0.0001$). The pooled results of these nine studies strongly indicate that patch reconstruction in general and saphenous vein in particular significantly reduce the probability of early internal carotid artery thrombosis, stroke, and restenosis compared with primary closure. The early thrombosis rate (0.2%), stroke rate (1.1%) and restenosis rate (1%) reported herein are comparable to the patch reconstruction rates of these studies. Although some component of clinical outcome for CEA is due to patient-related risk factors, it is clear that surgeon-related factors play a major role.[28] Patch reconstruction not only reduces the probability of a technical misadventure, with primary closure leading to postoperative thrombosis, embolization, or restenosis but, if performed with the goal of producing a hemodynamically optimal geometry patching, may also further improve short- and long-term clinical outcome.

These results may aid in the design of three-dimensional geometric theoretical and in vitro model hemodynamic studies. For example, the increased length of the internal carotid bulb may significantly alter the flow disturbances in the carotid bulb by separating the two major determinates of disturbed flow—the bifurcation and the step-down from the internal carotid bulb to the distal internal carotid artery. This is one potential explanation for the low rate of recurrent stenosis of patched CEA. The geometric changes in the common carotid bulb are of interest because this is where major flow disturbances occur, due to the branching of the common carotid artery into the internal and external carotid arteries.[9,10] The small increase in circumference and cross-sectional area of the common carotid bulb produced by patching, as well as the more round cross-section, may decrease flow disturbances. Numerical solutions of the fluid mechanics equations for a two-dimensional carotid bifurcation confirm the localization of flow disturbance at areas of plaque and myointimal development and predict the location of changes in internal carotid geometry due to wall thickening.[9,13] These equations have recently been solved for the optimal two-dimensional carotid geometry that minimizes shear stress–induced plaque mitigation,[10] and wall shear stress gradients.[14] The optimal design eliminates the bulb configuration of the common and internal carotid arteries and suggests a 15% to 30% gradual waist-type narrowing of the first segment of the internal carotid artery.[10,14] These two-dimensional theoretical results are in direct contrast to normal carotid artery geometry and to the way both classic synthetic and saphenous vein patch reconstructions change carotid geometry.[5,6] Three-dimensional in vitro flow models and theoretical solutions to the fluid mechanics equations are necessary to determine the optimal carotid artery geometry to minimize the hemodynamic factors that may be associated with localized development of atherosclerosis, myointimal hyperplasia, and thrombosis. Separating the hemodynamic effects of the bifurcation from that of the transition from internal carotid bulb to internal carotid artery, as is done by patch reconstruction, may favorably alter the hemodynamically produced propensity for thrombosis and restenosis but probably does not represent an optimal CEA reconstruction geometry. Customized CEA patch reconstruction with a tapered distal patch that uses both the shape of the patch and the depth of suture bites into the endarterectomized wall may produce a near-optimal hemodynamic geometry.[14] Some of the common carotid bulb diameters produced in this study are slightly larger than optimal, inasmuch as this dimension should be kept less than 13 to 14 mm to both minimize the degree of step-down to the uniform segment of internal carotid artery and, in this case of vein patch reconstruction, to decrease the chance of patch rupture.

REFERENCES

1. Archie JP. Prevention of early restenosis and thrombosis-occlusion after carotid endarterectomy by saphenous vein patch angioplasty. Stroke 1986;17:901-5.
2. Hertzer NR, Beven EG, O'Hara PJ, Krajewski LP. A prospective study of vein patch angioplasty during carotid endarterectomy. Ann Surg 1987;206:628-35.

3. Katz MM, Jones GT, Degenhardt J, Gunn B, Wilson J, Katz S. The use of patch angioplasty to alter the incidence of carotid restenosis following thromboendarterectomy. J Cardiovasc Surg (Torino) 1987;28:2-8.
4. Eikelboom BC, Ackerstaff RGA, Hoeneveld H, Ludwig JW, Teeuwen C, Vermeulen FE, et al. Benefits of carotid patching: a randomized study. J Vasc Surg 1988;7:240-7.
5. Clagett GP, Patterson CB, Fisher DF Jr, Fry RE, Eidt JF, Humble TH, et al. Vein patch versus primary closure for carotid endarterectomy. J Vasc Surg 1989;9:213-19.
6. Lord RSA, Raj TB, Stary DL, Nash PA, Gragam AR, Goh KH. Comparison of saphenous vein patch, polytetrafluoroethylene patch, and direct arteriotomy closure after carotid endarterectomy; part I: perioperative results. J Vasc Surg 1989;9:521-9.
7. Stein PD, Sabbah HN. Measured turbulence and its effect on thrombus formation. Circ Res 1974;35:608-13.
8. Goldsmith HL, Turitto VT. Rheological aspects of thrombosis and haemostasis: basic principles and applications. Thromb Haemost 1986;55:415-21.
9. Ku DN, Giddens DP, Zarins CK, Glagov S. Pulsatile flow and atherosclerosis in the human carotid bifurcation. Atherosclerosis 1985;5:293-302.
10. Kleinstreuer C, Nazemi M, Archie JP. Hemodynamics analysis of a stenosed carotid bifurcation and its plaque-mitigating design. J Biomech Eng 1991;113:330-5.
11. Chervu A, Moore WS. An overview of intimal hyperplasia. Surg Gynecol Obstet 1990;171:433-40.
12. Bandyk DF, Kaebnick HW, Adams MB, Towne JB. Turbulence occurring after carotid bifurcation endarterectomy: a harbinger of residual and recurrent carotid stenosis. J Vasc Surg 1988;7:261-8.
13. Nazemi M, Kleinstreuer C, Archie JP. Pulsatile laminar flow and plaque formation in a carotid artery bifurcation. J Biomech 1990;23:1031-5.
14. Wells DR, Archie JP, Kleinstreuer K. The effect of carotid artery geometry on the magnitude and distribution of wall shear stress gradients. J Vasc Surg 1996;23:667-78.
15. Lei M, Kleinstreuer C, Truskey GA. Numerical investigation and prediction of atherosclerotic sites in branching arteries. J Biomech Eng [in press].
16. Archie JP. The geometry and mechanics of saphenous vein patch angioplasty after carotid endarterectomy. Tex Heart Inst J 1987;14:395-9.
17. Archie JP. Carotid endarterectomy with reconstruction technique tailored to intraoperative findings. J Vasc Surg 1993; 17:141-9.
18. Archie JP, Green JJ. Saphenous vein rupture pressure, rupture stress, and carotid endarterectomy vein patch reconstruction. Surgery 1990;107:389-98.
19. Imparato AM. The carotid bifurcation plaque—a model for the study of atherosclerosis. J Vasc Surg 1986;3:249-55.
20. Imparato AM. The role of patch angioplasty after carotid endarterectomy. J Vasc Surg 1988;7:715-6.
21. Riles TS, Lamparello PJ, Giangola G, Imparato AM. Rupture of the vein patch: a rare complication of carotid endarterectomy. Surgery 1990;107:10-2.
22. Tawes RL, Treiman RL. Vein patch rupture after carotid endarterectomy: a survey of the western vascular society members. Ann Vasc Surg 1991;5:71-3.
23. O'Hara PJ, Hertzer NR, Krajewski LP, Beven EG. Saphenous vein patch rupture after carotid endarterectomy. J Vasc Surg 1992;15:504-9.
24. Archie JP. Carotid endarterectomy vein patch rupture revisited: selective utilization based on vein diameter. J Vasc Surg 1996;24:346-52.
25. Ranaboldo CJ, Bawros D'Sa AAB, Bell PRF, Chant ADB, Perry PM. Randomized controlled trial of patch angioplasty for carotid endarterectomy. Br J Surg 1993;80:1528-30.
26. Little JR, Bryerton BS, Furlan AJ. Saphenous vein patch grafts in carotid endarterectomy. J Neurosurg 1984; 61:743-7.
27. Katz MM, Jones GT, Degenhardt J, Gynn B, Wilson J, Katz S. The use of patch angioplasty to alter the incidence of carotid restenosis following thromboendarterectomy. J Cardiovasc Surg 1987;28:2-8.
28. Hertzer NR. The hidden statistics of carotid patch angioplasty. J Vasc Surg 1994;19:555-6.

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