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Computer Simulation and Geometric Design of Endarterectomized Carotid Artery Bifurcations

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ABSTRACT: The main goal of this computational study is to establish surgical guidelines for optimal geometries of carotid endarterectomy reconstructions that may measurably reduce postoperative complications, that is, thrombosis, stroke, and/or restenosis. The underlying hypotheses are that nonuniform hemodynamics, or "disturbed flows," are linked to arterial diseases and consequently that minimization of "disturbed flow" indicators leads to geometric bifurcation designs that lower postoperative complication rates. Considering transient 3-D laminar blood flow in partially occluded, in-plane, rigid-wall carotid artery bifurcations, the results presented include time-averaged indicators of "disturbed flow", such as the wall shear stress, spatial wall shear stress gradient, and wall shear stress angle deviation. In addition, trajectories and deposition patterns of critical blood particles (i.e., monocytes) are shown and evaluated. Within given physiological constraints, the vessel geometry was then changed in order to reduce the magnitudes of key indicators associated with thrombosis (i.e., blood clot formation) or restenosis (e.g., renewed atherosclerosis and/or hyperplasia). The quantitative results and knowledge base generated will be crucial for future clinical trials.

KEY WORDS: branching blood vessels, arterial diseases, particle-hemodynamics, numerical analysis.

I. INTRODUCTION

The carotid artery supplies blood via the internal carotid artery to the brain and through the external branch to the facial tissue. The carotid sinus, which is a site of major "plaque" formation in the internal carotid artery, is considered by many surgeons to be an anomaly. Thus, keeping the geometric inlet point and the two outlet points, the entire bifurcation could be redesigned based on the systematic reduction of one or more physico-biological indicator functions of arterial diseases.[1] Specifically, *atherosclerosis*, *thrombi formation*, and *intimal hyperplasia* are major causes of morbidity and mortality in Western civilizations, resulting in clinical problems such as stroke, heart attacks, or insufficient blood supply to other visceral organs and the extremities.

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Endarterectomy and bypass grafting have been used for four decades to eliminate or delay these events. For example, carotid endarterectomy for stroke prevention has a relatively low but significant 1 to 4% incidence of early postoperative internal carotid artery thrombosis, a 2 to 6% early stroke rate, and a 5 to 10% incidence of greater than 50% restenosis due to myointimal hyperplasia in the first few years and later due to recurrent atherosclerosis.[2,3]

Endarterectomy is applicable only to occlusive arterial lesions caused by atherosclerosis. At the proximal end of a carotid endarterectomy, there may be a step that is formed between the remaining atherosclerotic vessel surface and the plaque removed surface. It is speculated that early postoperative emboli originate on or from a common carotid step. In fact, no correlation between the presence of a step and both early postoperative emboli symptoms and severe late restenosis has been studied.[4] However, new geometric reconstructive recommendations assured improved hemodynamics and reduced the possibility of patch rupture.[5] The results of the computer optimization work discussed should further modify these recommendations and should lead to an improved, generally accepted technique of carotid endarterectomy reconstruction.

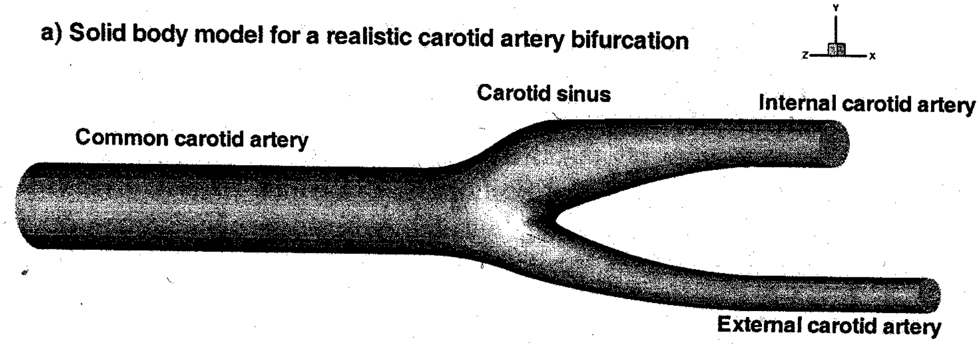
Several research groups have published clinical/experimental observations and numerical studies of blood flow and intimal thickening in carotid artery bifurcations. For example, the spatial and temporal characteristics of blood flow in a carotid bifurcation via in vitro and in vivo experimental measurements as well as computational simulations,[6,7] computational modeling in conjunction with computer-aided design as well as medical imaging techniques,[7,8] and the recommendation for the surgical reconstruction of the branching blood vessel[7] have been published. The underlying hypotheses and design methodology leading to branching blood vessels with high sustained patency rates are discussed elsewhere.[1,7]

II. THEORY

The blood vessel geometry of interest, that is, an asymmetric expansion step in the common carotid due to endarterectomy and the bifurcation of a typical carotid artery,[4] is best depicted with a solid body model using Pro/Engineer (cf. Figure 1a). Typical flow waveforms at the extended inlet and outlets are given in Figure 1b. The underlying assumptions are that blood flow is laminar and incompressible, all branches are rigid and in-plane, and the characteristics of non-Newtonian fluid can be described by a modified Casson model.[9] Thus, the governing equations for Eulerian fluid motion are the continuity equation and the equation of motion.[9]

Focusing on critical blood particles such as quasispherical monocytes (diameter $\approx 14\ \mu\text{m}$, volume fraction $O(10^{-7})$), the gravity, pressure, and Basset forces are negligible, because of the relative density ratio, whereas the interaction force is neglected due to the system being dilute. Also, Brownian motion may be ignored for the particles with $d_p > 1\ \mu\text{m}$. Hence, the particle trajectory equation can be described by Newton's second law.[9]

a) Solid body model for a realistic carotid artery bifurcation



b) Flow waveforms for the common, internal and external carotid arteries

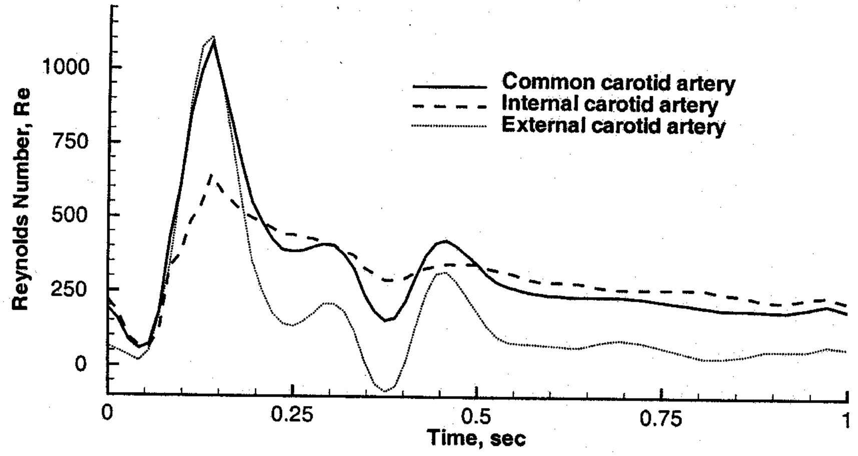


FIGURE 1. Solid model for a reference carotid artery bifurcation with flow waveforms.

In order to capture the aggravating effects of local disturbed flow patterns on the endothelium, several parametric functions indicating susceptible sites of arterial disease developments have been postulated. Key to most indicator functions is the wall shear stress (WSS), with which the spatial wall shear stress gradient (WSSG)[9] and the oscillatory shear index (OSI)[10] can be formulated. A new indicator, the wall shear stress angle deviation (WSSAD), was suggested by Kleinstreuer et al.,[7,9] which links aggravating hemodynamics with abnormal cell morphology as well as the normal velocity component (i.e., possible particle transport) near the wall. Now, sophisticated computational fluid dynamics software packages (e.g., CFX 4[11]-enhanced with user-supplied programs[7,9]) on high-performance computers make it possible to solve the transient three-dimensional fluid-particle flow problems for complex geometries.

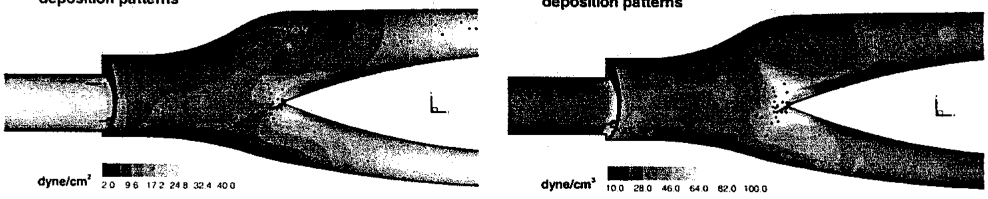
III. RESULTS

Of interest are the realistic carotid artery bifurcation (RCAB) shown in Figure 1, a typical endarterectomized carotid artery bifurcation (ECAB) and its two-step geometric design improvements, that is, a smoothing of the 90-degree step (SECAB) and then a more radical junction modification (ICAB), which gradually leads from the upstream point to the branch-end points. Because of space limitations, results are only shown for the ECAB and ICAB; additional simulation results are discussed elsewhere.[7,9] The particle deposition patterns as well as the WSS, WSSG, OSI, and WSSAD contours are shown, while the relative velocity fields and particle evolution patterns are given elsewhere.[7] It should be noted that the final particle deposition patterns are the same for a given input pulse and geometry, regardless of initial particle conditions.[7,9]

Quasi-equilibrium particle densities are highest at the vertical wall of the sudden expansion and in the carotid sinus due to reverse flow phenomena for the ECAB (cf. Figure 2). Direct particle impaction can be seen at the bifurcation (or stagnation) point and in the converging branch segments, especially the internal carotid artery. Lateral wall deposition occurs because of secondary, vertical flows upstream of the flow divider. These distinct particle deposition or near-wall aggregation sites are similar to areas of elevated WSSAD-values, which are the regions of the secondary flow toward the wall and the areas of significant changes in WSS vector direction (cf. Figure 2). The critical sites can also be predicted selectively by the other time-averaged *disturbed flow* indicators, which

a) Time-averaged |WSS| contour and blood particle deposition patterns

b) Time-averaged |WSSG| contour and blood particle deposition patterns



c) OSI contour and blood particle deposition patterns

d) WSSAD contour and blood particle deposition patterns

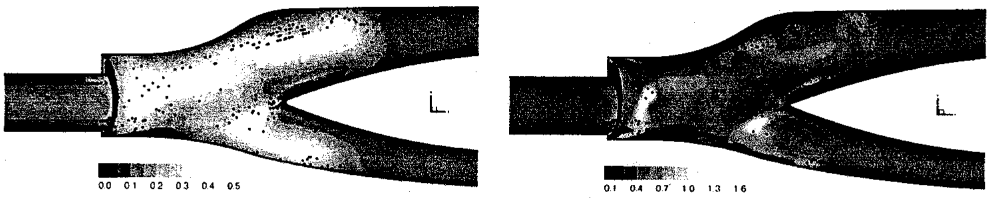


FIGURE 2. Time-averaged disturbed flow indicators with wall particle deposition patterns for the ECAB.

are the areas of low WSS magnitudes, elevated WSSG-values, and/or elevated OSI-values. For example, low WSS in conjunction with elevated WSSG can be used to predict particle deposition in the distal carotid sinus, external carotid artery, and at the flow divider. Elevated OSI-values alone can be used to predict some particle deposition on the lateral wall in the common carotid artery, in the distal carotid sinus and external carotid artery. However, they are not consistently useful for discriminating the susceptible regions of arterial diseases.

There are two basic approaches for designing blood vessel geometries, both relying on the minimization, or at least a reduction, of the single best indicator function or a severity parameter that combines several indicators. The first technique sets up an objective function subject to constraints and seeks an automated solution by employing a nonlinear multivariate optimization software in conjunction with an automatic mesh generator as part of the CFD solver. While still a bit utopian for complex problems, as the present one, it is recommended to employ a trial and error method guided by the same objective function and constraints as well as the physical insight gained from previous analyses. Surprisingly, variations in local step expansion geometry did not reduce the indicator functions.[18] Thus, an asymmetric conical expansion of the (diseased) common carotid artery is suggested in conjunction with an elimination of the sinus bulb and milder wall curvatures (cf. Figure 3). As a result, the time-averaged WSS-contour variations are smaller. The region of elevated WSSAD values in the internal carotid artery has almost disappeared, and the high WSSAD regions at the nondivider wall in the external carotid artery are reduced. Disturbed flow patterns are largely absent in disease-prone regions of the carotid sinus after the geometric improvements. Except the very focal region at the divider wall, the time-averaged WSSG appears uniformly low and the area of elevated WSSG-values is relatively small. Geometric changes do not affect the magnitude and trend of the OSI, which is strongly influenced by the input pulse. It is observed that the internal and external carotid arteries as well as the bifurcation region have elevated OSI values that are similar to other carotid artery bifurcations.[6,9] Nevertheless, further geometric improvements may be warranted once clinical trials with ICAB-like features have been concluded.

IV. CLINICAL OBSERVATIONS AND CONCLUSIONS

There are currently two major technical problems with carotid endarterectomies, that is, CEAs. The first is an incomplete endarterectomy end-point with residual atherosclerotic disease and the second is a reconstruction that produces adverse hemodynamic events. There are three endarterectomy end-points: the internal carotid, the common carotid, and the external carotid. A major objective of CEA is to obtain a complete internal carotid end-point. This can be achieved in greater than 97% of cases, but to do so requires that the arteriotomy incision be extended into the internal carotid distal to the bulb segment.[12] Unless the recon-

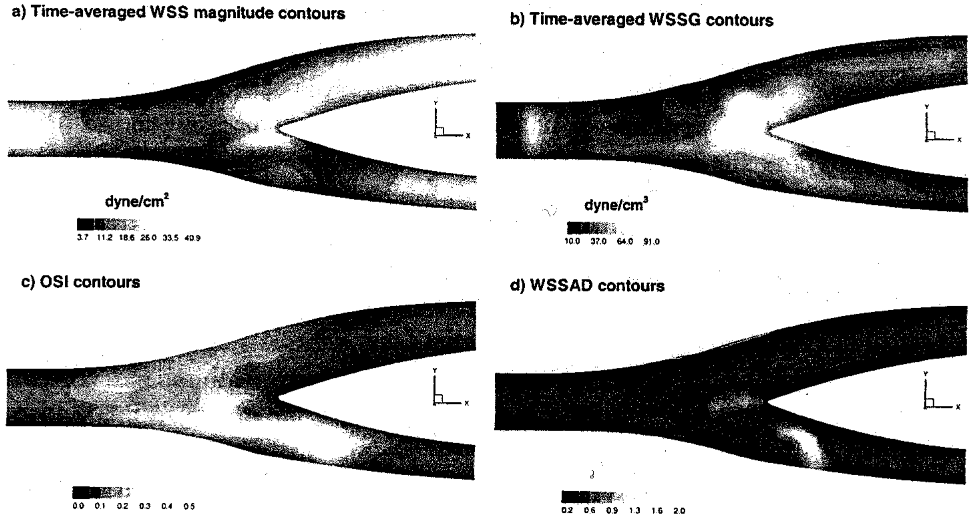
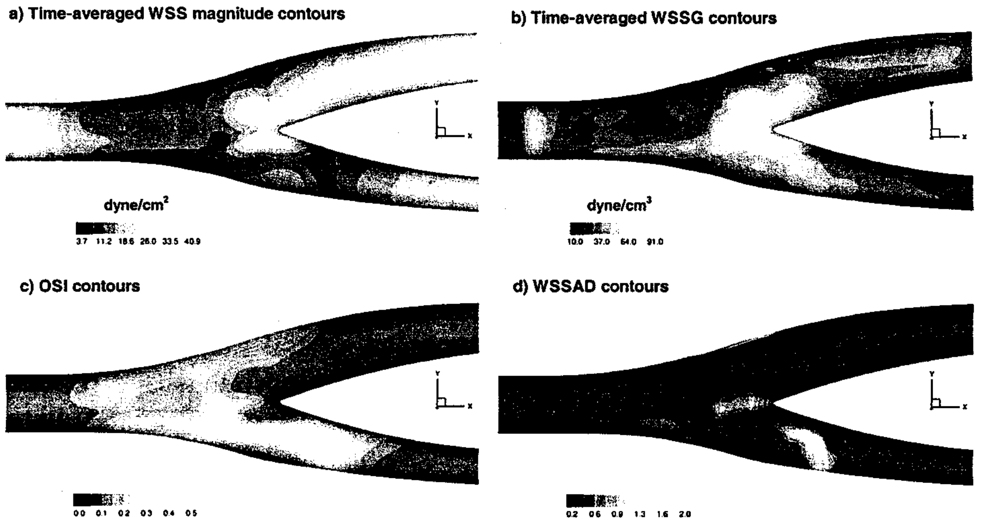


FIGURE 3. Time-averaged disturbed flow indicators for the ICAB.

struction is performed with a patch, a narrowing or stenosis is produced in the uniform diameter internal carotid artery. Primary suture closure of this arteriotomy results in a stenotic technical defect that can lead to further stenosis, thrombosis, or embolization. At the common carotid artery or proximal end of the endarterectomy, a complete end-point is rare because the atherosclerotic intima and media extends proximally, usually to the aorta. Circumferentially dividing this, results in a step or shelf as described earlier. The adverse hemodynamics produced by this technical defect can be surgically modified when necessary, usually when steps are ≥ 1 mm.[4] The external carotid endarterectomy end-point is usually produced blindly because this artery is not opened. The results of this approach to the external carotid leave a lot to be desired.[13]

The ideal carotid artery reconstruction (cf. ICAB) is in theory one that produces minimal flow disturbances. Currently, this is best achieved by obliteration of the carotid bulb, eversion plication reconstruction of the common carotid step ≥ 1 mm, and patch angioplasty with a gradually tapered reduction in internal carotid diameter from its origin to the distal end of the arteriotomy in the uniform diameter segment.[14] Our recent experience with this technique, as predicted by the solutions presented herein, is favorable with a perioperative stroke rate of 1.9% and a recurrent stenosis rate of 3% at 3 years when a saphenous vein patch is used.[15]

Carotid endarterectomy (CEA) with obligatory or highly frequent patch angioplasty reconstruction is the gold standard by which newer experimental techniques such as balloon angioplasty with or without stenting must be measured. CEA is a safe and durable prevention, particularly when surgical reconstructions follow the particle-hemodynamic guidelines discussed.



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