Analysis of atherosclerotic plaque geometry and wall motion in carotid arteries using 4D B-mode ultrasound and high resolution magnetic resonance angiography

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Introduction

Though significant progress has been made in diagnosis and treatment of atherosclerotic carotid artery disease, it still remains a major cause of stroke, one of the leading causes of morbidity and mortality in developed countries. Numerous experimental studies have provided convincing evidence that hemodynamics play a role as a localizing factor for atherosclerotic lesions, presumably reflecting response of the vessel wall to the adjacent flow field (2,10,17). Indeed it is known that such lesions are associated with areas of shear and recirculation, conditions which found on the non-divider wall in the carotid artery bifurcation, the predominant location of plaques (21). Studies on the natural history of carotid artery disease have shown that not all plaques are progressive, but that some remain stationary while others regress. This suggests that actual plaque geometry may influence hemodynamic conditions related to further plaque development, the termination of which may provide prognostic information for individual patients. It is therefore not surprising that there has been increasing interest in 3D plaque reconstruction.

In the foregoing discussion it is evident, however, that simple 3D reconstruction will provide adequate information to allow evaluation of complex hemodynamic interactions arising from changes in plaque geometry. For this purpose it is necessary to consider pulsatile flow dynamics and alterations of adjacent vessel wall segments, features which require an analysis of the temporal dimension. A 4D extension to evaluation of plaque geometry is therefore imperative.

Analysis of carotid artery wall motion could have important implications for furthering our knowledge on mechanisms of hemodynamic compromise and of carotid embolism. The role of wall motion in vessel segments adjacent to carotid plaques for embolic events is currently unknown. Both theoretical models and experimental evidence suggest that changes in arterial wall motion and even wall collapse occur distal to a stenosis (13). Such phenomena have yet to be demonstrated in patients with carotid artery disease, possibly due to a lack of appropriate methodology. Moreover, distinct differences in arterial diameter related to the time course of blood velocity have been shown to occur in patients with essential hypertension, a significant risk factor for atherosclerosis (9). To what degree such changes are related to plaque progression, embolic plaque phenomena or thrombotic occlusion is currently a matter of speculation (8). A clinical 4D methodology for wall motion analysis may contribute to elucidation of such phenomena.

The purpose of this study was therefore to establish a clinical method for 4D analysis of
atherosclerotic plaques, pulsatile dynamics and wall motion in carotid arteries to serve as a platform for investigations with finite element and finite difference methodology.

One prerequisite for numerical simulation of blood flow in carotid arteries is an exact geometry. For this purpose B-mode ultrasound, a noninvasive and routine clinical technique which offers excellent display of carotid arteries, is the imaging method of choice. Moreover, considerable progress has been made in the field of 3D ultrasound over the last several years (5,14,18) and reports on 3D plaque reconstruction at the carotid bifurcation have shown the feasibility of this technique (20).

The importance of pulsatile flow upon features such as separation, secondary flow and flow disturbances has been elegantly demonstrated with hydrogen bubble flow visualization and laser-Doppler-velocimetry (10,11). The question of which functional imaging procedure is best suited for providing pulsatile flow information for integration with morphological data from ultrasound is not easily answered. The necessity of obtaining an accurate insonation angle makes Doppler a poor choice for 3D examination, while this angle will be constantly changing during the procedure. More promising seems to be the combination of B-mode ultrasound with new magnetic resonance angiographic techniques.

Numerous methods using MR for determination and evaluation of blood flow velocity and volume flow have been described. Nearly all of these techniques fall into two categories; first phase contrast (PC) methods (changes in proton phase dependent on flow velocity), and time-of-flight (TOF) related methods. A new method, dynamic MR bolus tracking, is a combination of MR flow presaturation and MR cine angiography for measurement of flow velocity (3,16). It is based on gradient-echo pulse sequences with cardiac triggering, small flip angle and short repetition time, in which signal suppression through presaturation results in a very low signal intensity in the ensuing images. This technique can be used to define volumes of presaturation, so that the signal of flowing volume leads to the formation of a bolus, whose spatial and temporal evolution can be followed.

Methods
Parallel B-mode ultrasound scans of the carotid artery (slice distance 2 mm, resolution 0.17 mm x 0.5 mm) triggered by presampled ECG R waves (10 frames per cardiac cycle) were achieved with a 7.5 MHz linear array probe (Acuson) and a mechanical step motor (Tomographic Technologies) in normal subjects and in patients with carotid artery plaques.

For segmentation of the 4D data set Gaussian convolutions were implemented to reduce artifacts, particularly those due to reverberation. Lateral shadowing was manually removed and those portions of the touched image were marked for exclusion in wall motion analysis. A nearest-neighbor thresholded classification algorithm was then used to segment the preprocessed data. Plaque segmentation involved additional definition of region of interest.

The magnitude and direction of carotid artery wall motion was measured by comparison of segmented ultrasound axial slices over time. Areas where manual segmentation was employed were disregarded in the analysis.

High resolution MR angiography utilizing magnetization transfer suppression and tilted optimized non-saturated excitation technique was performed using a Siemens Magnetom 63 SP 1.5 T magnet system. For MR bolus tracking cardiac-triggered gradient echo pulse sequences with additional presaturation pulses (TR/TE/flip/FOV/matrix/Aq. - 95ms/20ms/30deg/230mm/160*256/1, 40ms/10ms/30deg/200mm/256*256/1), partly in multi-echo technique with a section thickness of 10 mm were accomplished. These sequences were used for acquisition of 32 images within the cardiac cycle. Flow velocity was calculated by measuring the distance of the spatial inflow of bright blood into the user-
defined rectangular presaturation volume over the interval of time between the presaturation and the image acquisition. These measurements allow calculation of peak flow velocities in systolic-diastolic modulation. Each data point in these spectra represents one inflow measurement at a definite time in the cardiac cycle. Volume flow can then be calculated by fitting the approximate parabolic velocity flow profile and three-dimensional integration of the spatial inflow over the time interval between presaturation and acquisition of each of the 32 measurements after the ECG R-wave.

Matching of the velocity flow profile obtained from bolus tracking to the segmented 4D ultrasound data set was accomplished through segmentation of the MRA data with a nearest-neighbor classification algorithm, data scaling, and center line registration between segmented ultrasound and MRA carotid arteries. This consequently enabled registration of the bolus tracking data to ultrasound.

Volume rendering and surface reconstruction was performed with the Application Visualization System (Advanced Visual Systems, Inc.) on a HP 715-50 CRX24Z workstation. Visualization of wall motion was achieved through animation of isosurface reconstructions.

Results

The described technique provides excellent visualization of 4D plaque geometry. The visualization of adjacent wall segments, however, was poor due to shadowing caused by plaque calcification.

Segmentation proved to be a tedious task for ultrasound data as it required viewing each 2D image slice individually for manual removal of lateral shadows and extreme reverberation artifacts.

Results show differences in wall motility in patients with symptomatic plaques. This was particularly evident distal to the stenosis and occurred predominantly on the wall of the flow divider. The wall adjacent to the flow divider and just distal to the stenosis showed little motion. Wall motion was best appreciated with the isosurface reconstruction.

Segmentation of MRA data sets proved to be a relatively straightforward task. Center line registration of bolus tracking velocity profile information to ultrasound data was achieved, although the accuracy of this method was questionable due to problems encountered with ultrasound segmentation.

Discussion

The results of this study show that 4D ultrasound is capable of delivering useful information on plaque geometry. Moreover, this method can detect changes in wall motion, although this feature is limited by problems of image acquisition primarily arising from artifacts. These problems might be overcome by employing a six degree of freedom electromagnetic tracking device instead of a mechanical step motor. Although the problem of reconstruction is quite complex for 6DOF, significant progress has been made in this area (5). Another approach might be to consider the implementation of B-spline algorithms for segmentation purposes (6).

The pulsatile blood flow through a 3D arterial bifurcation can be described by the time-dependent 3D Navier-Stokes equations. The numerical solution of these equations, an arduous computer task, makes use of either finite difference or finite element approaches. While each method has its advantages and disadvantages, it seems that a finite difference method applied on a finite element mesh may provide the best overall results (15).

Early work in numerical simulation of flow adopted highly simplified symmetric models while later effort was devoted to geometric modeling of the carotid bifurcation based on biplanar angiograms (1). Numerical studies dealing with flow in an asymmetric three-dimensional bifurcation with complex geometry are limited and there have been no reports on using such methodology in a clinical setting. Likewise, only a few studies have
considered the effect of wall elasticity and non-Newtonian viscoelasticity of blood on flow fields at bifurcations (19, 12). These have demonstrated substantial differences of secondary flows and flow separation behind the bifurcation as compared to models not incorporating these features.

It is obvious that numerical simulation of blood flow using clinical data from ultrasound and MR bolus tracking will be a difficult task. This endeavor, however, is certain to provide valuable insights into the pathophysiology of stroke and atherosclerosis and will continue to be a central area of research at our institution.

References


