The Carotid Bifurcation As A Blood Flow Pulsatility Low-Pass Filter Characterized by Magnetic Resonance Phase Contrast Flow Quantitation Methods

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Introduction

The carotid bifurcation is very much like other vascular forks in that is has a single input signal (the common carotid artery (CCA) and two output signals (external carotid (ECA) and internal carotid (ICA) arteries. However, it is unique in that the proximal segment of only one branch (the ICA) is a dilatation known as the "carotid bulb" – an area of known complex flow patterns and neurovascular sensors. Additionally, we observed that the flow in the ICA distal to the bulb and the flow across a comparable location in the ECA, was markedly less pulsatile in terms of the volume flow rate (VFR-mls/sec). Did the bulb cause a change, or "filter" the pulsatility? The effects of blood flow pulsatility (volume flow rate amplitude range variation during a given cardiac cycle) in a given vascular bed may affect levels of turbulence and thrombus formation at the carotid bifurcation, the origination point for 70% of the cerebral circulation via the internal carotid artery (ICA) (Hademenos). Carotid Bifurcation geometry has been characterized to some degree (Bharadvaj, Fanucci). Carotid bifurcation hemodynamics have been measured using MR phase contrast methods (Bendel). This research hypothesized that the carotid bifurcation bulb is a hemodynamic volume flow rate, pulsatility damping, low-pass filter. Additionally, it also hypothesized that bifurcation vessel lumen geometry mediated this "smoothing" process.

Methods

A normal human test population comprising 12 females, 18 males, (ages: 20-60 years) resulted in 30 carotid bifurcations. This effort occurred in four stages: 1) MRA acquisition of structural and flow measurement vascular image sets, 2) digital image processing to yield two-dimensional geometric measurements representing three defined structural classes: integral (global) structure, confluence (local), and carotid bulb (local) geometry, 3) post-processing of hemodynamic flow quantification data were used to compute both time domain (volume flow rate (VFR) waveforms, pulsatility/smoothing indices) and frequency domain (bulb and non-bulb-related) transfer functions. 4) finally, statistical analysis used the resulting geometric and hemodynamic datasets to show significant interrelationships.

All acquisitions were preformed using a 3-inch TMJ coil placed on the lateral surfaces of the neck approximating the level of the carotid bifurcation. A cardiac-gated time-of-flight pulse sequence (TR: 35o, TE: 6.9, views-per-segment: 4-8, flip angle: 35*,FOV:12 cm, thickness: 2.5 mm, NEX: 1) , prescribed in the plane of the each bifurcation, was used to obtain oblique slice images which were then MIP´d into frames representing a given phase of the cardiac cycle. The cardiac phase image approximating peak systole was chosen to allow digitized 2D digital measurements. A cardiac-gated phase contrast sequence (TR: 35, TE: 7.3, VENC: 100 cm/sec, views-per-segment: 4-8, flip angle: 35*,FOV: cm, thickness: 3 mm, NEX: 1) was used to obtain mean arterial blood flow velocites at points on the common carotid, external carotid and internal carotid arteries. Velocities and luminal cross-sectional areas for the cardiac phases of each vessel´s phase contrast images were automatically segmented using a statistical method involving the Mahalanobis distance. The volume flow rate (VFR) for each vessel was computed from the luminal areas and mean velocities. From the VFR data, tme-domain pulsatility [M3P = (sd(ICA)/mean(CCA)] and smoothing [M1P = (sd(predicted ICA- measured ICA)/mean(CCA)] indices were computed for each vessel from the VFR waveforms. Also, Fourier transforms generated both magnitude and phase shift frequency response transfer functions (0-14 Hz.) for the non-bulb-related and bulb-related pathways in the bifurcation. The relationships between bifurcation luminal geometry, the hemodynamic time- and hemodynamic frequency domain functions were analyzed using linear regression.

Results

VFR pulsatility damping effects had significant relationships with the hemodynamics of the carotid bifurcation. Linear relationships between vascular geometry, the time- and frequency- domains proved to be primarily significant for two 2D geometric measurements: The Bifurcation Index$_{diamter}$ [(BI=ECA+ICA)/CCA)], and the bulb inlet diameter (IIN). Two pulsatility smoothing effects were evident. Effect 1: as the bifurcation index value increased, smoothing increased (M3P decreased/M1P increased) and only bulb-related transfer function magnitude and phase values showed low-pass filtering effects (magnitude decreases: 2-3 Hz., phase difference increases: 2 Hz.). Effect 2: as the bulb inlet diameter increased, smoothing increased (M3P decreased/M1P increased) and only bulb-related transfer function magnitude and phase values showed low-pass filtering effects (magnitude decreases: 2-3 Hz., phase angle increases: 3 Hz.). Figures 1 illustrates the weak inverse correlation betwen the smoothing and pulsatility indexes as well as their relationships to the bifurcation index and bulb inlet diameter. Thus, two geometric parameters mediated overall, simultaneous smoothing effects in a linear manner, both in the time- and frequency-domains: the bifurcation index (globally) and the bulb inlet diameter (locally).

Discussion

A fluid mechanics vascular impedance model accounted for the contrasting smoothing effects observed. The local bulb mechanism emphasizes the inductive and capacitive components of vascular impedance due to the bulb's complex geometry and increased distensibility. The global bifurcation smoothing mechanism emphasizes the non-frequency resistance component of vascular impedance - the compliance and inductive forces were considered insignificant. This above model accounts for the effects seen. Therefore, the global mechanism sets the level of naturally-occurring pulsatility for the entire bifurcation, while the carotid bulb simultaneously applies low-pass filtering, smoothing the internal carotid arterial flow only.

References

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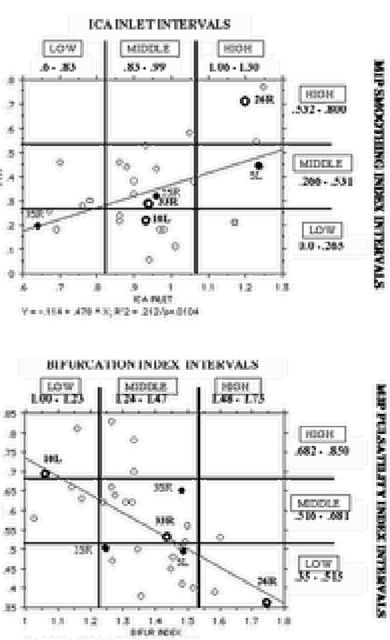

Figure 1