ANALYSIS OF FLOW DISTURBANCE DUE TO STENOSED CAROTID ARTERY WALL

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I dedicate this thesis to my beloved family, Abah, Emak, Kak Syuhada, Kak Qila, Raihan, Imran and Naqiu. This thesis is also dedicated to my supervisors, Dr Ishkrizat Taib and Dr Nofrizalidris Darlis.

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ABSTRACT

Carotid arteries with specific structural and anatomical abnormalities due to dolichoarteriopathies (DA) has been reported to influence the arterial haemodynamic flow patterns which could lead to the development of regions prone to carotid artery stenosis (CAS). Therefore, this study was conducted to determine the haemodynamic behaviour of different carotid artery morphologies with various degrees of stenosis. Six different carotid artery morphologies were constructed, which then afflicted with 20%, 40%, 60% and 80% stenosis. Through the use of the computational fluid dynamic (CFD) method via commercial software, the simulations were performed under two physiological conditions; normal blood pressure (NBP) and high blood pressure (HBP). The haemodynamic behaviour was evaluated using several parameters, specifically the time-averaged wall shear stress (TAWSS), time-averaged wall shear stress gradient (TAWSSG), oscillatory shear index (OSI) and relative residence time (RRT). Subsequently, the morphology haemodynamic behaviour was analysed using a selection method. Based on the observation, the TAWSS, TAWSSG and OSI increase along with the degree of stenosis, whereas RRT had an inversely proportional relationship with stenosis severity. The presence of stenosis coupled with obvious curvature of carotid morphology further disturbed the haemodynamic flow. In all cases, Type I displayed the best haemodynamic behaviour with and without the presence of stenosis. On the other hand, Type IV showed the most affected haemodynamic behaviour due to its morphology, stenosis existence and increase in blood pressure. Yet, with 60% and 80% degree of stenosis affliction, Type II presented the most disturbed blood flow pattern. Type III, V and VI showed moderate haemodynamic behaviour for both physiological conditions and when afflicted with stenosis. In conclusion, different flow re-circulation at the different bifurcated stenotic carotid morphologies (BSCM) has a significant effect on the stenosis growth.

ABSTRAK

Arteri karotid dengan keabnormalan struktur dan anatomi akibat dolichoareriopathies (DA) telah dilaporkan mempengaruhi corak aliran hemodinamik arteri yang boleh menyebabkan pengembangan kawasan yang terdedah kepada arteri karotid stenosis (CAS). Oleh itu, kajian ini dijalankan untuk menentukan tingkah laku hemodinamik pada morfologi arteri karotid yang berbeza dengan pelbagai darjah stenosis. Enam morfologi arteri karotid berbeza telah dibina kemudiannya diletakkan stenosis 20%, 40%, 60% dan 80%. Melalui penggunaan kaedah pengkomputeran dinamik bendalir (*CFD*) melalui perisian komersial, simulasi dilakukan di bawah dua keadaan fisiologi; tekanan darah normal (*NBP*) dan tekanan darah tinggi (*HBP*). Tingkah laku hemodinamik dinilai menggunakan beberapa parameter khususnya purata masa tegasan ricih dinding (*TAWSS*), purata masa kecerunan tegasan ricih dinding (*TAWSSG*), indeks osilasi ricih (*OSI*) dan masa kediaman relatif (*RRT*). Seterusnya, morfologi tingkah laku hemodinamik dianalisis menggunakan kaedah pemilihan. Berdasarkan pemerhatian, *TAWSS*, *TAWSSG* dan OSI meningkat seiring dengan tahap stenosis manakala hubungan *RRT* berkadar songsang dengan keterukan stenosis. Kehadiran stenosis dan kelengkungan di morfologi karotid, terus mengganggu aliran hemodinamik. Dalam semua kes, Type I memaparkan tingkah laku hemodinamik terbaik dengan dan tanpa kehadiran stenosis. Sebaliknya, Type IV menunjukkan tingkah laku hemodinamik yang paling terjejas disebabkan oleh morfologi, kewujudan stenosis dan peningkatan tekanan darah. Namun, pada 60% dan 80% darjah stenosis, Type II menunjukkan corak aliran darah yang paling terganggu. Type III, V dan VI menunjukkan tingkah laku hemodinamik sederhana untuk kedua-dua keadaan fisiologi dan apabila mengalami stenosis. Kesimpulannya, peredaran semula aliran yang berbeza pada morfologi stenotik karotid dwicabang yang berbeza (BSCM) mempunyai kesan yang signifikan terhadap pertumbuhan stenosis.

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4.49 OSI distribution at (a) anterior (b) posterior of carotid artery afflicted with 80% stenosis for HBP condition 122
4.50 RRT distribution at (a) anterior (b) posterior of healthy carotid artery for NBP condition 125
4.51 RRT distribution at (a) anterior (b) posterior of healthy carotid artery for HBP condition 126
4.52 RRT distribution at (a) anterior (b) posterior of carotid artery afflicted with 20% stenosis for NBP condition 128
4.53 RRT distribution at (a) anterior (b) posterior of carotid artery afflicted with 40% stenosis for NBP condition 129
4.54 RRT distribution at (a) anterior (b) posterior of carotid artery afflicted with 60% stenosis for NBP condition 130
4.55 RRT distribution at (a) anterior (b) posterior of carotid artery afflicted with 80% stenosis for NBP condition 131
4.56 RRT distribution at (a) anterior (b) posterior of carotid artery afflicted with 20% stenosis for HBP condition 132
4.57 RRT distribution at (a) anterior (b) posterior of carotid artery afflicted with 40% stenosis for HBP condition 133
4.58 RRT distribution at (a) anterior (b) posterior of carotid artery afflicted with 60% stenosis for HBP condition 134
4.59 RRT distribution at (a) anterior (b) posterior of carotid artery afflicted with 80% stenosis for HBP condition 135

LIST OF SYMBOLS AND ABBREVIATIONS

Ne	-	Normalised relative error
Vc	-	velocity in the current mesh setting
Vp	-	velocity in the previous mesh configuration
ρ	-	*density*
μ	-	*viscosity*
Re	-	Reynolds number
V	-	velocity magnitude
a_0	-	Initial empirical parameter *a*
a_n	-	Empirical parameter *a* at *n*th number
b_n	-	Empirical parameter *b* at *n*th number
ω	-	Angular frequency
w	-	Weightage
F	-	Fourier function
$\vec{g}$	-	Gravitational acceleration vector
τ	-	Shear stress
K	-	Kurtosis
t, T	-	Time
V	-	Velocity magnitude
$\vec{V}$	-	Velocity vector
α	-	Blood flow direction
β	-	Normal to blood flow direction
μ_d	-	Dynamic viscosity
Q	-	blood flow rate
r	-	lumen radius
$\overrightarrow{\tau}_{ij}$	-	Fluid viscous stress tensor
$\vec{n}$	-	Normal vector

∇	-	Gradient operator
μ	-	mean
σ	-	Standard deviation
K	-	Kurtosis
A_i	-	Surface area of face *I*
φ_i	-	Haemodynamic characteristics at face *i*
φ_{perc}	-	Area distribution percentage of haemodynamic parameter
φ_{ref}	-	Reference area distribution percentage of haemodynamic parameter
φ_{PC}	-	Percentage change
$\varphi_{highest}$	-	The highest variable performance
φ_{lowest}	-	The lowest variable performance
S_j	-	Weighted score summation
d	-	End-diastolic
D	-	Peak-diastolic
i_1	-	First incisura
i_2	-	Second incisura
Rt	-	Rating
S_1	-	Peak-systolic
S_2	-	Second systolic
Θ	-	Angle

CAS - Carotid artery stenosis

ICA - Internal carotid artery

DA - Dolichoarteriopathies

CFD - Computational fluid dynamic

NBP - Normal blood pressure

HBP - High blood pressure

TAWSS -Time-averaged wall shear stress

$TAWSS_{low}$ - Low time-averaged wall shear stress

$TAWSS_{norm}$ - Normal time-averaged wall shear stress

$TAWSS_{high}$ - High time-averaged wall shear stress

TAWSSG - Time-averaged wall shear stress gradient

OSI - Oscillatory shear index

RRT - Relative residence time

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