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Haemodynamics Analysis of Carotid Artery Stenosis and Carotid Artery Stenting

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Declaration of originality

I hereby declare that this thesis and the work presented in it are my own as the result of my own investigation except where stated otherwise. This thesis has not been submitted in whole or in part to another university for the award of any other degree or professional qualification.

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Abstract

Carotid stenosis is a local narrowing of the carotid artery, and is usually found in the internal carotid artery. The presence of a high-degree stenosis in a carotid artery may provoke transition from laminar to turbulent flow during part of the cardiac cycle. Turbulence in blood flow can influence haemodynamic parameters such as velocity profiles, shear stress and pressure, which are important in wall remodelling. Patients with severe stenosis could be treated with a minimally invasive clinical procedure, carotid artery stenting (CAS). Although CAS has been widely adopted in clinical practice, the complication of in-stent restenosis (ISR) has been reported after CAS. The incidence of ISR is influenced by stent characteristics and vessel geometry, and correlates strongly with regions of neointimal hyperplasia (NH). Therefore, the main purpose of this study is to provide more insights into the haemodynamics in stenosed carotid artery and in post-CAS geometries via computational simulation.

The first part of the thesis presents a computational study on flow features in a stenotic carotid artery bifurcation using two computational approaches, large eddy simulation (LES) and Reynolds-averaged Navier-Stokes (RANS) incorporating the Shear Stress Transport model with the γ-Re_θ transition (SST-Tran) models. The computed flow patterns are compared with those measured with particle image velocimetry (PIV). The results show that both SST-Tran and LES can predict the PIV results reasonably well, but LES is more accurate especially at locations distal to the stenosis where flow is highly disturbed.

The second part of the thesis is to determine how stent strut design may influence the development of ISR at the carotid artery bifurcation following CAS. Key parameters that can be indicative of ISR are obtained for different stent designs and compared; these include low and oscillating wall shear stress (WSS), high residence time, and wall stress. A computationally efficient methodology is employed to reproduce stent strut geometry. This method facilitates the accurate reconstruction of actual stent geometry and details of strut configuration and its inclusion in the fluid domain. Computational simulations for flow patterns and low-density lipoprotein (LDL) transport are carried out in order to investigate spatial and temporal variations of WSS and LDL accumulation in the stented carotid geometries. Furthermore, finite element (FE) analysis is performed to evaluate the wall stress distribution with different stent designs. The results reveal that the closed-cell stent design is more likely to create atheroprone and procoagulant flow conditions, causing larger area to be exposed to low wall shear stress (WSS), elevated oscillatory shear index, as well as to induce higher wall stress compared to the open-cell stent design. This study also demonstrates the suitability of SST-Tran and LES models in capturing the presence of complex flow patterns in post-stenotic region.

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Nomenclature

Abbreviations

ACAS	Asymptomatic Carotid Atherosclerosis Study
ACST	Asymptomatic Carotid Surgery Trial
BEM	Boundary element method
CAD	Computed aided design
CAS	Carotid artery stenting
CCA	Common carotid artery
CEA	Carotid endarterectomy
CFD	Computational fluid dynamics
CREST	Carotid revascularization endarterectomy versus stenting trial
CT	Computed tomography
CV	Control volumes
CVD	Cardiovascular disease
DNS	Direct numerical simulation
dSm	Dynamic Smagorinsky
DUS	Doppler ultrasound
ECA	External carotid artery
ECST	European Carotid Surgery Trial
EPF	Embolic protection filter
FDM	Finite difference method
FEM	Finite element method
FSI	Fluid-structure interaction
FVM	Finite volume method
ICA	Internal carotid artery
ISR	In-stent restenosis
LAM	Longitudinal anatomic mismatch
LDL	low-density lipoprotein
LES	Large eddy simulation
MI	Myocardial infarction

MRI	Magnetic resonance images
NASCET	North American Symptomatic Carotid Trial
NH	Neointimal hyperplasia
NHS	National Health Service
NIP	Neointimal profileration
OSI	Oscillatory shear index
PDE	Partial differential equations
PIV	Particle image velocimetry
POD	Particle orthogonal decomposition
RANS	Reynolds-averaged Navier-Stokes
RRT	Relative residence time
RSM	Reynolds stress model
SGS	Subgrid-scale
SMC	Smooth muscle cell
SST	Shear Stress Transport
TAWSS	Time-averaged wall shear stress
TIA	Transient ischemic stroke
TKE	Turbulent kinetic energy
Tu	Turbulence intensity
VMS	Von Mises stress
WSS	Wall shear stress

Roman Symbols

$\bar{S}_{ij}$	Large-scale strain rate tensor
$\bar{U}$	Average velocity component
$\hat{G}$	Grid filter
3-EWM	3-element Windkessel model
$\mathbf{F}$	Body forces per unit mass
$\mathbf{T}$	Viscous stress tensor
$\mathbf{u}$	Velocity
$\tilde{G}$	Test filter
L_{ij}	Resolved turbulent stress
C_s	Smagorinsky constant
C	Model constant
D	Vessel luminal diameter
F_1	Blending function
F_2	Blending function
J_s	Transmural velocity
J_v	Solute flux
k	Turbulent kinetic energy
R	Arterial radius

S_{ij}	Strain-rate tensor
T	Cardiac cycle period
u'	Velocity fluctuation
U	Mean velocity
u	time-varying velocity component
G	Filter function
H_t	Haematocrit
$\mathrm{R}\hat{e}$	Peak Reynolds number
Re	Reynolds number
Re_T	Viscosity ratio
Re_v	Strain-rate Reynolds number
Re_θ	Momentum thickness Reynolds number
$\mathrm{Re}_{\theta c}$	Critical momentum thickness Reynolds number
t	time
y^+	Viscous wall unit, wall distance

Greek Symbols

α	Womersley parameter
β	Closure coefficient
Δ	Filter width
δ	Stokes layer thickness
δ_{ij}	Kronecker delta
$\dot{\gamma}$	Shear rate
ϵ	Dissipation per unit mass
γ	Intermittency
μ	Viscosity
μ_p	Plasma viscosity
μ_T	Dynamic eddy viscosity
ν	Kinematic viscosity
ν_T	Kinematic eddy viscosity
ν_T	Subgrid-scale turbulent viscosity
Ω	Vorticity magnitude
ω	Angular frequency
ω	Specific dissipation rate
ϕ	Closure coefficient
ρ	Density
σ	Closure coefficient
σ_D	Osmotic reflection coefficient
σ_f	Solver reflection coefficient
τ_w	wall shear stress
τ_{ij}	Reynolds-stress tensor

τ_{ij}	Subgrid-scale stress tensor
τ_{mean}	Mean shear stress
θ	Momentum thickness
σ_{ω}	Closure coefficient
σ_k	Closure coefficient
a_1	Closure coefficient
c_{γ}	Closure coefficient

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