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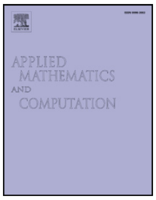

Noninvasive assessment of carotid artery stenoses by the principle of multiscale modelling of non-Newtonian blood flow in patient-specific models

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ABSTRACT

The concept of geometrical multiscale modelling of non-Newtonian blood flow in patient-specific models is presented with the aim to provide a methodology for the assessment of hemodynamic significance of carotid artery stenoses. The content of the paper is divided into two consequent parts. In the first one, the principle of the fractional flow reserve (FFR) as an indicator of ischemia-inducing arterial stenoses is tested on three large arterial models containing the aortic arch and both left and right carotid arteries. Using the three-element Windkessel model as an outflow boundary condition, the blood flow simulations are carried out on the basis of data taken from the literature due to unavailable information on patient-specific flow and pressure waveforms. In the second part of the paper, the incorporation of real in-vivo measurements into the multiscale simulations is addressed by presenting a sequential algorithm for the estimation of Windkessel parameters. The ability of the described estimation method, which employs a non-linear state estimator (unscented Kalman filter) on zero-dimensional flow models, is demonstrated on two different patient-specific carotid bifurcation models.

1. Introduction

In recent years, the computer-aided imaging methods, such as computed tomography (CT) in combination with mathematical modelling, have opened up new possibilities in diagnosis and treatment of cardiovascular diseases. As extensively discussed, e.g., in [1], the use of computational fluid dynamics (CFD) modelling within cardiovascular medicine promises to be of particular benefit not only during the design of new stents and valve prostheses, but also as a tool for non-invasive patient assessment. As an example, it is possible to mention the difficulties associated with the determination of clinical and hemodynamic significance of arterial stenoses of intermediate severity (40–70% reduction in lumen diameter). Given the nature of current clinical decision-making regarding surgical intervention, which in the case of intermediate stenoses is mostly carried out on the basis of surgeons' experience and/or additional tests, the contribution of CFD modelling could be substantial as it is able to provide potentially valuable information on pressure and flow fields that would be either difficult to obtain (depending on the patient's medical condition) or would be unachievable by any available clinical technique.

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Nomenclature

C	capacitance/compliance
C_a	arterial compliance
C_{fsi}	inlet capacitance
C_t	total arterial compliance
L	inductance
p	pressure
p_{bif}	bifurcation pressure
p_d	distal pressure
p_{dia}	diastolic pressure
p_{ext}	external pressure
p_{sys}	systolic pressure
Q	flow rate
R	resistance
R_p	proximal resistance
R_d	distal resistance
R_t	total arterial resistance
t	time
x	state vector, Eqs. (24)–(25)
z	observation vector
Δ_{sys}	coefficient in Eq. (10)
λ	vector of parameters
Φ_{PP}	coefficient in Eq. (10)
ψ	constrained quantity, Eq. (13)
ψ_{ref}	reference value, Eq. (13)
$\hat{\psi}$	unconstrained quantity, Eq. (13)
$\psi^{(s)}$	quantity associated with the sth outlet

Abbreviations and indices:

0D	zero-dimensional
3D	three-dimensional
CC	common carotid artery
CFD	computational fluid dynamics
CT	computed tomography
EC	external carotid artery
FFR	fractional flow reserve
$\mathrm{FFR_{CT}}$	FFR derived from CT, Eq. (14)
FSI	fluid-structure interaction
IC	internal carotid artery
MAP	mean arterial pressure
PC-MRI	phase contrast magnetic resonance imaging
UKF	unscented Kalman filter

The benefits of cardiovascular CFD modelling regarding physiological assessment of stenosis severity can be already found in clinical practice, specifically in regard to coronary arteries as demonstrated by the results from the DeFACTO [2], VIRTU-1 [3], and NXT [4] studies/trials. In this case, the CFD modelling is involved in the determination of the fractional flow reserve (FFR)—an established clinical parameter defined as the ratio between pressure distal to a coronary artery stenosis and aortic pressure under conditions of maximum myocardial hyperaemia (drug-induced reduction of microvasculature resistance), see Section 5.1. Despite the fact that FFR is able to identify a hemodynamically significant coronary stenosis ($\mathrm{FFR} \leq 0.8$) with an accuracy of more than 90% [5], its invasive nature, involving insertion of a pressure wire during catheterisation, makes it impractical for widespread use, especially in elderly patients. Thus, in an effort to avoid unnecessary burden on patients and to reduce healthcare costs, an alternative non-invasive technique for the determination of vascular pressures has been developed. In clinical practice, this technique known as FFR derived from CT ($\mathrm{FFR_{CT}}$) [2] or as 'virtual' FFR (vFFR) [1] is essentially based on numerical results obtained from multiscale CFD simulations in patient-specific vascular models [6].

Although clinical FFR is primarily determined in coronary arteries, its principle is also applicable to peripheral vasculature [7,8] despite the fact that a standardised procedure for the measurement of peripheral FFR has yet to be clinically established. In this case, the difficulty lies in the induction of hyperaemia as the correct drug-dosage in peripheral arteries is still unknown [9]. A potentially promising solution to this problem can be seen in multiscale CFD modelling, which employs the patient's unique anatomy and physiology without the need for an invasive induction of hyperaemia.

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