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論　文　内　容　の　要　旨

氏　　名	（ Mohd Azrul Hisham Bin Mohd Adib ）
論文題名	A new concept of data assimilation method between PC-MRI measurement and CFD simulation of blood flow analysis on patient-specific cerebral aneurysm （患者個別の脳動脈瘤に対する血流解析のPC-MRI計測とCFDシミュレーションを用いた新たなデータ同化手法の概念）

論文内容の要旨

Computational fluid dynamics (CFD) analysis has been extensively performed to investigate patient-specific blood flow fields and hemodynamics factors on the cerebral aneurysm。 There are two key issues for the patient-specific CFD simulation; one is realistic vessel geometry、 and the other is boundary condition。 Meanwhile、 the cerebral aneurysm often develops at the bifurcation of cerebral arteries、 so the analysis of the model with multiple outlet boundaries remains a critical issue。 On the other hand、 according to the advancement in medical imaging technique、 blood flow field is able to be obtained invasively using phase contrast magnetic resonance imaging (PC-MRI)。 Unfortunately、 since the current spatial resolution of the PC-MRI is insufficient to reproduce the blood flow field in cerebral vessels with a diameter of a few millimeters、 with directly using PC-MRI velocity profile。 In this regard、 various approaches to combine the numerical simulation and measurement data、 so-called data assimilation (DA) have been recently developed for blood flow problems。 This thesis conducts a computational approach based data assimilation on reducing the velocity differences between the PC-MRI measurement and the CFD simulation on the patient-specific aneurysm。

In the first part of the thesis、 the effects of extracted patient-specific geometries with different threshold image intensities on flow solution were investigated by using CFD studies。 The reconstruction of the vessel geometries was derived using the determination threshold coefficient (Cthres) method and the blood flow analyses were conducted by a pressure fixed (P-fixed) approach and flow-rate control (Q-control) approach、 where expresses the outlet boundary in CFD analysis as an ad hoc outlet pressure and adjustment the outlet pressure by modified the flow rate difference respectively。 The results exhibited that the inlet area and volume of the vascular model decrease as the value Cthres increases、 whereas the wall shear stress (WSS) distribution increases as Cthres increases。 The minimum velocity difference between PC-MRI measurement and CFD simulation was obtained at a Cthres value of 0。3。 This relationship potentially gives the physically adequate realistic vessel geometry to achieve the minimum value of velocity difference on flow fields for each patient。

Next、 the study was focused to propose a basic framework for imposing a pressure condition on the outlet boundary in order to minimize the velocity differences between PC-MRI measurement and CFD simulation。 The velocity-field optimized (V-optimized) approach was proposed to couple velocity fields in the measurement and computation、 in which a set of pressure values on outlet boundary is determined based on an optimization problem。 This present approach solves the direct problem iteratively。 To evaluate the effects of imposing the outlet pressure、 this P-fixed approach、 Q-control approach、 and V-optimized approach (the present approach) were compared。 The result showed that、 the highest reduction in velocity difference occurs at the V-optimized approach、 where the velocity difference (normalized by inlet velocity) is 19。3%。 This present approach also confirmed that the differences in boundary treatments affect the WSS values in both local domains for an aneurysm and non-aneurysm region。

For the consideration of improvement on the exhaustive search to find the optimal solution in V-optimized approach、 a novel data assimilation method for patient-specific blood flow analysis based on conventional feedback control theory called the physically consistent feedback control-based data assimilation (PFC-DA) method was proposed。 In the PFC-DA method、 the signal was attributed to a residual velocity difference between the numerical and measured velocities、 which is cast as a source term in a Poisson equation for the potential scalar field that induces flow in a closed system。 The pressure values at the inlet and outlet boundaries are recursively calculated by this potential scalar field。 Through the feasibility study on the PFC-DA method demonstrated the flow was automatically separated into respective daughter branches by determining the boundary pressure and the higher resolution in computational mesh provides the WSS profile。 As compared with the proposed V-optimized approach、 although this PFC-DA method does not guarantee the optimal solution、 only one additional Poisson equation for the scalar potential is required、 providing an improvement for such a small additional computational cost。 These achievements clearly exhibit a huge potential of the new direction in patient-specific PC-MRI integrated blood flow analysis for a cerebral aneurysm。

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論文審査の結果の要旨及び担当者

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論文審査の結果の要旨

本論文は、MRIにより計測された血管形状や血流速度に基づいて、脳動脈瘤血管内の血流動態を数値流体解析により再現するデータ同化手法についての研究成果をまとめたものである。まず、血管造影したMRI画像からの脳動脈の血管形状の抽出が血流の数値解析に及ぼす影響について検討を行い、位相コントラストMRIによって得られる血流速度を最もよく再現する血管形状の抽出パラメタを求めた。つぎに、血流解析における流出部の圧力境界条件が、数値流体解析結果と計測データとの誤差に及ぼす影響について検討を行った。従来の研究では、個別に得られた血管形状に対しても同一の生理的な血圧状態を仮定したり、計測された流出部における血流量を一致させるような境界条件を設定することが行われてきたが、本研究では、位相コントラストMRIによって得られる血管領域内のすべての血流速度データを用いて、計算結果との誤差の総和を最小にする新しいデータ同化手法の考え方を提案した。逐次探索法で最適な圧力境界条件を求めた結果、10例の脳動脈瘤血管の実形状モデルにおいて、数値流体解析で得られた血流速度と計測結果との誤差を20%以下にすることができた。さらに、計測値と計算値との血流速度の誤差をナビアストークスの式の外力項として与える従来のフィードバック法の定式化を改良し、血流速度の誤差を速度ポテンシャルで表現することにより、補正する外力項の物理的意義を明らかにし、繰り返し計算により流出部の圧力境界条件を補正する実用的なデータ同化手法を構築した。これにより、計測データと数値流体解析とを融合して、患者個別の脳動脈瘤血管の血行力学的因子を評価できる解析手法を確立し、臨床で得られた実形状モデルに適用してその実行可能性を示した。脳動脈瘤が成長して破裂に至ると、生命に重大な危機を及ぼすくも膜下出血を引き起こす。動脈瘤の発症および成長には血行力学因子が関与していると考えられており、本研究で確立したデータ同化手法は、計測を重視する臨床診断の中で患者個別の血行力学因子を正しく評価し、診断や治療に活用していく数値流体解析技術として極めて重要である。その解析手法および得られた知見をまとめた本論文は、博士（工学）の学位論文として価値のあるものと認める。