A Grid Based e-Research Platform for Clinical Management in the Human Respiratory and Vascular System

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Abstract

A Grid based e-Research platform is being developed for providing a simulation-based virtual reality environment for clinical management and therapy treatment. The development of this platform involves cross-disciplinary experts aiming at combining the state-of-the-art Computational Fluid Dynamics (CFD) analysis tools into clinical management system. These fluid dynamic studies support the physician and surgeon with recommendations for the possible range of treatment and operation techniques. The platform will consist of a cluster of computing nodes, a middleware (Grid management layer), internet accessible tomography data and CFD analysis tools, and a tailored graphical user interface (GUI) application for various experts. In future, this platform will provide the novel creation of a prototype virtual reality model environment that links each technical modular consisting of a consolidation system with flexible interface model for exchanging data efficiently. Furthermore, besides allowing expeditious sharing of data and analytical tools, it will also furnish a foundation for cross-disciplinary collaboration and will definitely foster further advancement of related biomechanics researches.

Keywords: Grid computing, E-research, Clinical management.

1 Introduction

Biomechanics is one of the fastest growing research areas in biomedical sector. Benefit from the recent development of High Resolution Computed Tomography (HRCT), Magnetic Resonance Image (MRI) and Computational Fluid Dynamics (CFD) technique, it is becoming feasible to develop an integrated platform supported by grid computing technique providing a simulation-based virtual reality environment for clinical management and therapy treatment in the human respiratory and vascular circulatory system. The platform enables surgeon or physicians to equitably share tomography data and fluid dynamics analytical tools that assist them to forecast outcomes of various therapeutical methods. Moreover, it also facilitates the opportunity to re-assess previously collected data fostering new medicine interpretations and insights.

The conceptual framework of the integrated platform is illustrated in Figure 1. The foundation of this platform involves the integration of high-level multi-disciplinary areas such as Grid Computing for better use of High Performance Computing (HPC) and Information Communication Technology (ICT) resources, Computer Aided Design – Geometry Reconstruction (CAD-GR), Computational Fluid Dynamics (CFD), data management and networking and Medical Informatics. Such platform relies on many facets of advanced computational and mathematical approaches for simulating airflow/blood flow in order to treat diseases of the respiratory and vascular system of a patient.

With the support of the Australian Research Council (ARC) E-Research program, modelled after the UK e-Science programme, we have initiated a cross-disciplinary project to develop and establish an E-Platform tailored for providing a simulation-based virtual reality environment for clinical management and therapy treatment in the human respiratory and vascular system. One significant feature of the development of this environment is the ability for surgeon or physician to adequately plan their treatment or operation decision-making of respiratory or vascular diseases. Conventionally, this clinical management or decision-making process is largely based on diagnostic imaging, experience and empirical data,

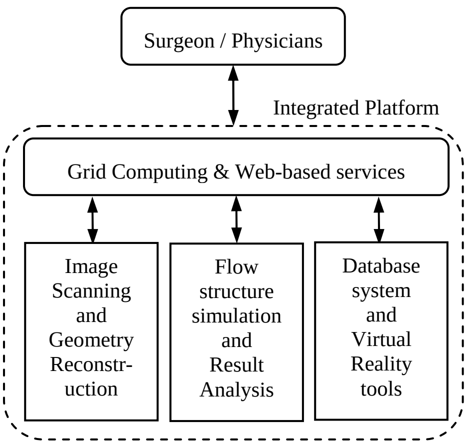

Figure 1: Conceptual framework of the integrated platform for clinical management.

which are insufficient to predict the outcome of a given treatment for an individual patient because of the multitude of therapeutic or operational choices. The E-Platform can be used to support the physician and surgeon with recommendations from a set of possible treatment and operation techniques in particular from the point of view of flow analysis using state-of-the-art CFD techniques. This can provide the surgeon or physician an effective tool for the diagnosis and treatment of diseases of the respiratory and vascular system and a new paradigm for the surgery planning, which can, in a long term, make medical procedures more predictive in the future.

2 Integrated platform – Advancement in Clinical Management

Owing to the significant advancements in computer technologies, a full-scaled model can be constructed integrating the various functional biological elements, e.g. the nasal, oral, laryngeal and generations of the bifurcation for the human respiratory airway system through state-of-the-art fine resolution imagining methodologies. A significant advantage of this human model is that the differences in airway morphology and ventilation parameters that exist between healthy and diseased airways, and other factors, can be accommodated. The physical model will allow numerical modellers to perform extensive numerical studies to probe significant insights to the flow characteristics within the complex airway passages (or vascular branches) and better understanding of any important phenomena associated with the fluid flow. Clinical management could benefit from the state-of-the-art CFD simulations that would provide unprecedented diagnostic information for the specific geometry of patient as determined by imaging. Since differences in airway/vascular morphology and parameters exist between healthy and diseased parts, even between adults and children, man and women, experimental evaluation of each specific type of geometry or factor cannot be undertaken as a practical measure; computational models need therefore to be sensibly employed. Through these computational models, the premise of better monitoring of diseases and dissecting information for clinical diagnosis and therapy for new methods of treatment can be realised. Also, the course of treatment directed specifically to the cause of sickness can be selected without a multitude of physical examinations. More importantly, the success or failure of interventional therapies that rely on altering the dynamics of flow within the respiratory system and vascular circulatory system is determined remotely without any physical tests or intrusions on the human body.

Preliminary successes, as demonstrated in coming sections, have been achieved in adopting the integrated approach to study the human respiratory and vascular circulatory systems. Nevertheless, we are confronted with a number of major difficulties whilst employing this approach. The human respiratory and vascular circulatory systems are by nature extremely complex. One difficulty for the construction of the CFD model is the attempt to resolve all the associated geometrical intricacies within the systems. The imaging process constitutes the tracking of large amount of data in mimicking all these complexities inherent within the geometrical structures. During the process of handling of these data, it had been found that not all the available data obtained from the imaging process can be directly and readily used to generate the appropriate CFD mesh but rather it requires laborious manipulation, which is intensely time-consuming. During the pre-processing stage, an optimal mesh for the CFD model is generally unattainable and therefore leads to huge usage of computational resources takes large

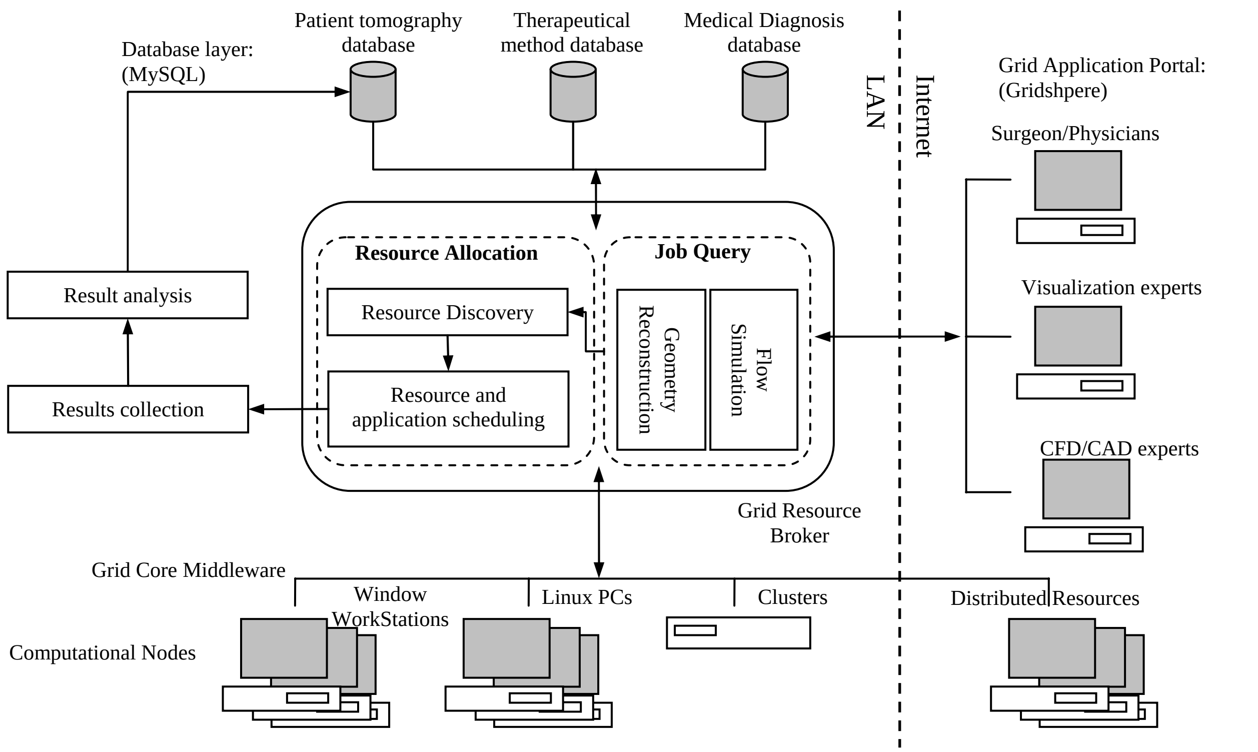

Figure 2: Architecture of grid computing facilities for the E-Platform.

computational time. Owing to the large computations, the post-processing of the CFD data may also be a very resource-intensive process. The visualisation and technical interpretation of the fluid dynamics behaviour during the post-processing stage to be easily understood for recommended medical diagnosis remains the greatest challenge and presents the missing link for information-sharing between the highly-skilled people that performed the CFD calculations and medical practitioners.

3 Methodology

For spaning the gap between CAD/CFD, Visualization and Medical expertise, a better acceleration solution algorithm, more efficient numerical and data-transfer technique, highly robust CFD model to better capture the flow characteristics within the human respiratory and vascular circulatory systems should be developed and consolidated into a single efficient clinical management platform.

The development of such complex platform requires successful integration of a range of computational systems (such as intelligent database analysis system, CAD/CFD and HPC system, virtual reality system) into a coherent Knowledge-based Interpretation and Recommendation (KIR) system that demands intensive involvement of a wide range of expertise. The development of the E-Platform has been strategically assembled multi-disciplinary developers and users; including experts from Engineering, Mathematics, Computer Science, Biological, Medical and Health Sciences, and Clinical Surgeon/Physicians. Within the platform, large volume of HRCT/MRI standardized tomography data are firstly stored and managed into image databases within the platform. Supported by the computational power and networking technology of the Grid computing, geometrical reconstruction procedures and CFD simulations are then performed for each patient's tomography images to generate an anatomically realistic 3D models and analyse the complex fluid dynamics in a patient-specific manner. The aforementioned data access and computational procedures will be supported and managed through seamless Grid computing facilities which are capable of running on multiple operating systems including Solaris/UNIX, Mac OS-X and Window 2000/XP proposed by Buyya and co-workers (Buyya and Venugpoal, 2004; Buyya et al., 2004).

The analysed simulation results obtained from CFD simulations will then be stored into the originating patient-specific database allowing surgeon/physicians remotely access the data from anywhere on the Internet for medical diagnosis. The E-Platform should therefore consist of a cluster of computing nodes, a middleware (Grid management layer), internet accessible tomography data and CFD analysis tools, and a tailored graphical user interface (GUI) application for users (the KIR system). Architecture of such E-Platform driven by grid computing infrastructure is shown in Figure 2.

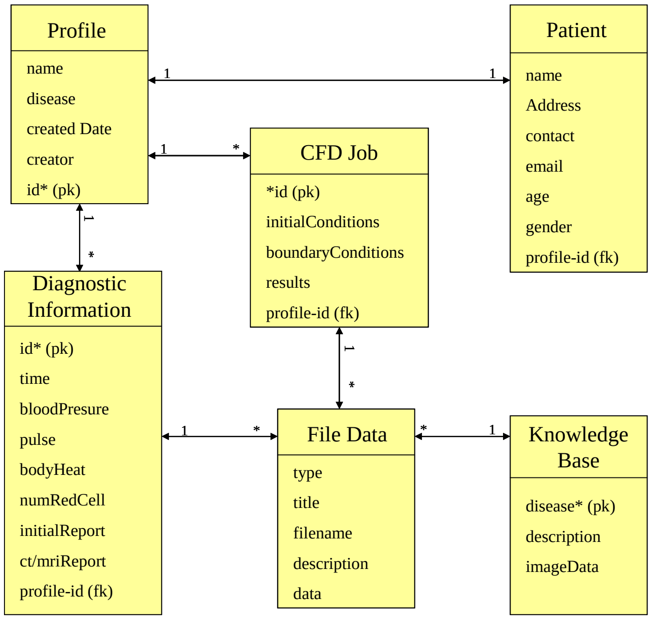

Figure 3: Fundamental Database model.

3.1 Data Persistence Mechanism

To handle large volume of HRCT/MRI standardized tomography data with our system which is built based on Java techniques, the approach to design and implement the data persistence is very important to the whole system affecting the both performance and complexity. Object/Relational Mapping solution such as Hibernate appears an excellent approach to deal with data persistence. It represents the relational table in the database as an object view to the developer, which is much easier to program using Java language. By adopting Hibernate to develop the data persistence logic, it significantly reduces the potential errors and code redundancy. Furthermore, if necessary in future development, we can easily change the underlying database and generate tables by simply modifying the XML configuration file.

Figure 3 illustrates the basic model employed for representing the underlying database tables. Individual XML meta file is adopted to describe the schema information for each table and one java object representation accordingly. With the Object-Oriented approach, developers / programmers only need to manage the Java object created for each table rather than parsing the table columns directly via the SQL queries.

3.2 Grid Resource Broker

In the geometry reconstruction procedures and CFD simulations, as discussed in the coming sections, it demands intensively computational power and resources. The platform should therefore be able to distribute computing operations/jobs dynamically to the remote Grid resources such as clusters or servers. A user-level middleware is also required to handle the complicated tasks including job composition, use QoS (Quality of Service) requirements, scheduling and monitoring is very important. We have planned to utilize Gridbus Broker (Nadiminti et al., 2005), which is an economic based resource broker supporting heterogeneous resources such

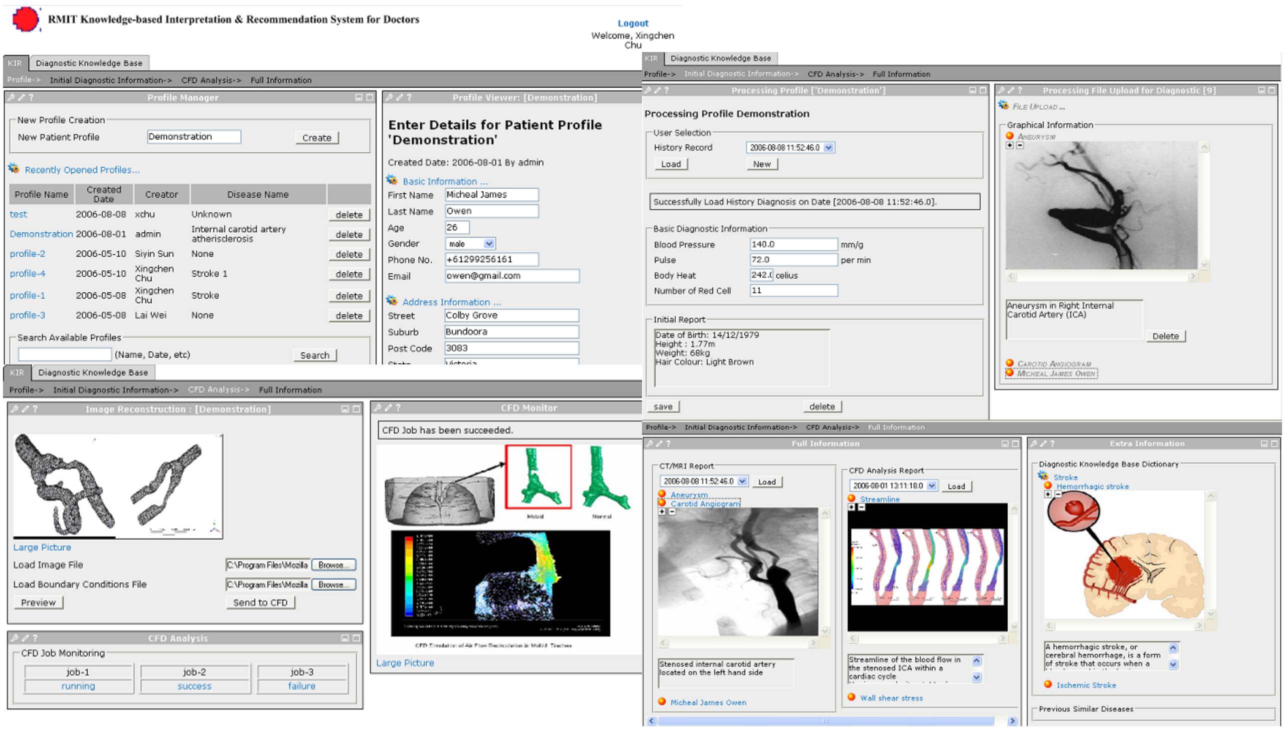

Figure 4: Graphical User Interface of the KIR Web Portal.

as: Globus, Condor, Alchemi and UNICORE. In order to fulfil the requirements of distributing jobs over grid resources, a job submission plug-in for the broker will be developed to enable the broker interacts with the computational servers. Moreover, the broker can be used seamlessly to support our platform.

3.3 KIR System – Graphical User Interface

To facilitate direct access to the HRCT/MRI image, reconstructed geometry model and flow simulation results for various group of experts, graphical user interface (GUI) has been developed using GridSphere portal framework (Gridsphere, 2006). Gridsphere is not only a mature framework which has been employed for several grid related portal developments, but it also provides reusable components such as user management, credential management, resources management via GridPortlet (Russell et al., 2006). More importantly, it is compatible with the widely adopted JSR 168 standard. Therefore, the portal can be easily deployed into any JSR 168 compatible server which largely increases the portability of the portal. In addition, Gridsphere also supports the integration of JavaServer Faces (JavaServer Faces Technology, 2006), the most popular technique that is capable of supporting visual tools to develop the portal.

A snapshot of KIR Web portal has been shown in Figure 4. The portal provides direct access of patient-specific medical data such as: initial diagnosis report, HRCT/MRI imaging data and associated medical history. Through the portal, surgeon/physicians are also allowed to create, edit or renew medical data of individual patient that is automatically synchronized with database.

An advanced feature of the portal will be provide to the CAD/CFD experts is the capability of allowing users to specify the desired calculations or simulations via its graphical interface. The portal will then compose the jobs and dispatch the jobs to the remote clusters or servers via the Grid Resource Broker. Execution monitoring service will also be provided for the users remotely supervise the status of the running jobs on the remote servers. Once jobs have completed, the results will be collected back to the portal server or maybe some data host so that they can be post-processed and visualized to the users.

In addition, the portal also provides a way to the user to manage the common knowledge base of the diseases providing the essential knowledge to both doctors and the system users. The knowledge base is equitably shared among users which contains both textual and image information of the most common diseases such as: Asthma or Stroke. Using information search function provided in the portal, the end users are able to extract the common knowledge and compare with the patient's diagnostic information in the database.

4 Clinical Applications – Flow modelling in Human Respiratory and Vascular Circulatory System

The key objective of the development of E-Platform is targeted on congregating wide range of research expertise and experiences into the clinical management. In parallel with the development of grid computing services, research works have been also preformed to investigate fluid flow structure in anatomically realistic human respiratory or vascular circulatory system. Preliminary successes have been achieved and will be briefly discussed in the following sections.

4.1 Anatomical Geometry Reconstruction

One crucial step in modelling flow characteristics within the complex airway passages or vascular branches is transforming the HRCT/MRI geometric information into an anatomically realistic three-dimensional computational model. Some of studies have been carried out are related to the geometric reconstruction procedures (Howatson et al. 2000, Long et al., 2000 and Long et al., 2003). Recently, in collaboration with Monash University, high resolution in vivo three dimensional data sets of human respiratory airway and artery architecture have been obtained. The segmented data consists of a series of high quality

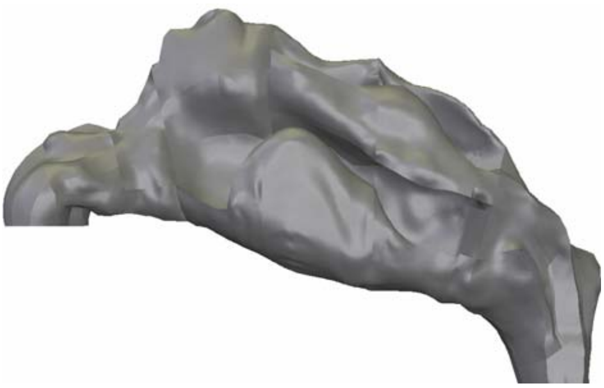

Figure 5: Reconstructed human nasal cavity model from HRCT images.

contours 2D images. Image segmentation processes were performed to extract and smooth the boundaries of the airway/artery from contours images. 3D structure of the geometric model was then generated by arranging the smooth contours in the axial direction. Although individual contour has been smoothed prior, the resultant 3D surface of the geometric model could still be rather rough.

Smoothing processes were then applied to improve the quality of the 3D configuration. The smoothing procedures involve two main steps: smoothing is firstly applied in the axial direction in order to reduce the registration error introduced from scanning procedures; the second step aims at correcting the inconsistency between two neighbouring contours. A reconstructed three-dimensional CAD model of a human nasal cavity is shown in Figure 5. However, computational capability required for such smoothing procedures is high. Moreover, at the moment, procedures execution requires professional intervention of CAD experts and collaboration with medical practitioners. Information flow between two parties becomes the bottom-neck of the whole process. In future, with the successful development of the E-Platform, increased computational power and database management of the gird architecture will allow a more efficient, time effective data exchange and smoothing procedures calculation.

4.2 Drug delivery in Respiratory system

With the generated anatomically realistic model, it is now possible to model the complex fluid dynamic behaviours associated with the human respiratory system. One particular application is modelling drug delivery and deposition in respiratory system. The human upper respiratory tract is the premier site of deposition of particles inhaled via the mouth/nose as well as acting as an important defensive shield to protect the lungs through the reduction of particle penetration to the more distal airways. Inhalation of drug particles deposited directly to the lung periphery results in rapid absorption across bronchopulmonary mucosal membranes and reduction of the adverse reactions in the therapy of asthma and other respiratory disorders (Smith et al., 1987). For this purpose, it is desirable that the particles should not deposit in the upper airways before reaching the lung periphery. This is because excessive deposition of drug particles in the upper airways will cause less therapeutic effects in the lung or local side effects in the upper conducting airways, which may lead to considerable additional treatment costs and reduce adherence to treatment.

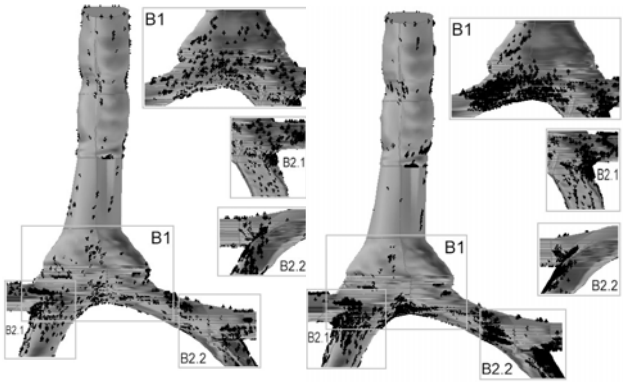

Figure 6: Drug deposition pattern in front and back view of airway with particle diameter in 10µm (left) and 20µm (left). (Square windows are the back view of the bifurcation).

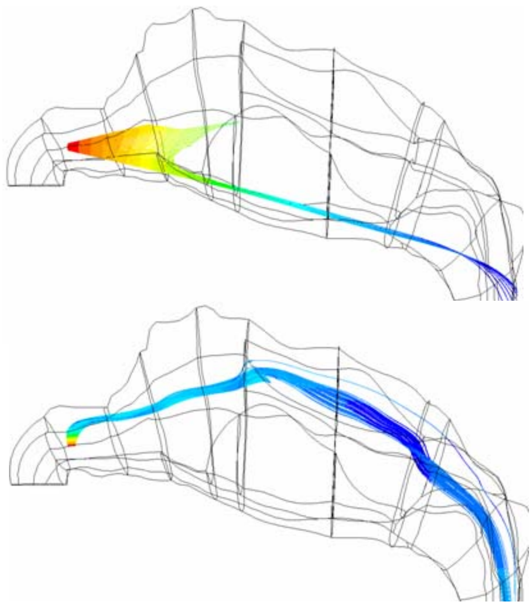

Figure 7: Drug particle trajectories in the nasal cavity: particle diameter of 20µm with 90 degrees injection angel (top), 10µm with 0 degrees injection angel.

By adopting the state-of-art CFD techniques, we successfully modelled the flow structure and drug particle transport/dispersion along the airway (Choi et al., 2006). The drug deposition pattern of two different drug particle sizes along the airway is depicted in Figure 6. Simulation results revealed that the drug particle diameter has a direct effect on its deposition location. Smaller drug particles, with less mass of each particle, trend to follow the main flow structure and dispersed more evenly within the airway. Using the simulation tool, an innovative, optimum and cost-effective drug delivery prototype system can be tested and accessed in a virtual-reality mean. This cost-effective approach can be also applied for testing drug delivery prototype systems for human nasal cavity. One of our numerical simulation results showing the drug particle trajectories and deposition locations in an anatomically realistic nasal cavity has been shown in Figure 7 (Tu et al., 2004, Inthavong et al., 2006).

4.3 Vascular Circulatory System

Another clinical application of the E-Platform is investigating the hemodynamic factors and blood flow structure in human vascular circulatory system. In well developed countries, the majority of deaths are mostly associated with some abnormal blood flow in arteries. For example, stroke is a major cause of mortality and morbidity in the aging Australian population. A major predisposing factor for ischemic stroke is atherosclerosis. Complex blood flow dynamics is thought to play a key role in the development and treatment of atherosclerosis; however, the exact nature of this role is incompletely understood owing to the practical difficulties associated with measuring important local hemodynamic factors, notably wall shear stresses, in vivo (Greil, et al., 2003). Detection and quantification of the abnormal blood flow in arteries serve as the basis for surgical intervention. This is critical if we are to map the hemodynamic factors that potentially underlie atherosclerosis in a prospective, patient-specific manner and to understand the effects of mechanical and pharmacological interventions.

To obtain crucial information on the blood flow is often rather difficult. With a realistic artery model reconstructed from MRI scan, we have successfully simulated the blood flow structure of stenosed and healthy carotid artery using CFD in a patient-specific manner. Figure 8 shows the time dependent wall shear stress (WSS) distribution on the circumference of the blood vessels of the two carotid artery models. Flow structure analysis shown that the distribution of the WSS is in accordance with the location of the stenosis (plaque formation due to atherosclerosis). It further affirmed that low WSS values are possibly correlated to localization of atherosclerotic lesions.

5 Conclusion and Future Work

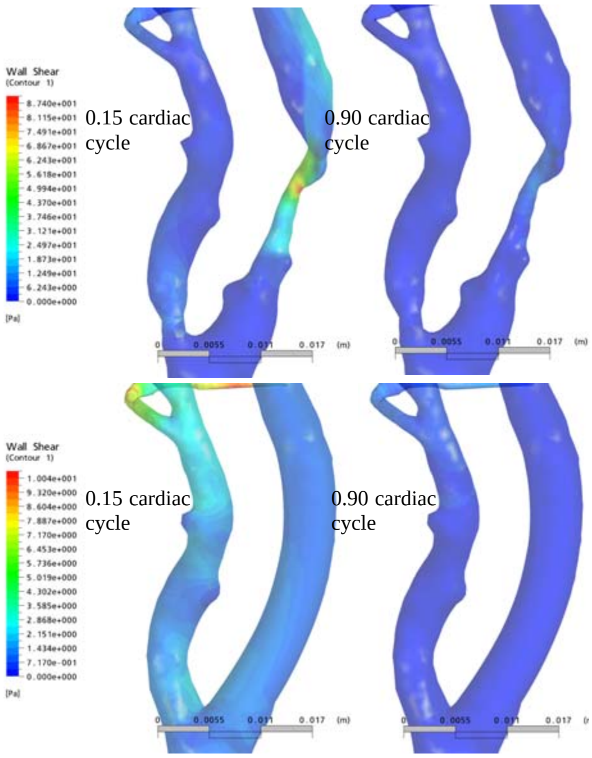

Figure 8: Time dependent wall shear stress distribution of a stenosed carotid artery: stenosed model (top) and healthy model (bottom).

With the support of E-research Grant program of Australian Research Council, a Grid based platform (E-Platform) is being developed for providing a simulation-based virtual reality environment for clinical management and therapy treatment in the human respiratory and vascular system. The platform allows surgeon, physicians and CAD/CFD experts to share tomography data and fluid dynamics analytical tools that assist them to forecast outcomes of various therapeutical methods. The E-Platform will consist of a cluster of computing nodes, a middleware (Grid management layer), internet accessible tomography data and CFD analysis tools, and a tailored graphical user interface (GUI) application for various users.

We have successfully implemented KIR-Web portal interacting with the database. Currently, we are working towards enhancing the portal to support online access to CFD-based analysis modules deployed on remote Grid resources as per the architecture discussed earlier. With the integration of the advanced flow modelling techniques with other high-level multi-disciplinary areas, this platform will be capable to handle distributed e-diagnosis and treatments. Furthermore, besides allowing rapid sharing of data and analytical tools, the platform will support cross-disciplinary collaboration and will definitely foster further advancement of related biomechanics researches.

Analogue to the geometry reconstruction procedures, aforementioned CFD simulations demand intensive computational power and resources. To gain full advantage of the increase computational power available from the Grid architecture, CFD jobs will be distributed to the remote clusters or servers, which are part of local and Australian National Grid. Furthermore, understanding the effects of mechanical and pharmacological interventions requires insights and expertise in medical as well as in mechanical area. More effective mean of sharing airflow / blood flow simulation results using Grid resources will definitely foster further advancement of related biomechanics researches.

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