INTEGRATED MODELING OF HUMAN CARDIOVASCULAR SYSTEM FOR THE CLINICAL APPLICATION OF COMPUTATIONAL FLUID MECHANICS

Tomoaki Hayasaka,
Department of Bioengineering and Robotics, School of Engineering
Tohoku University
Sendai 980-8579, Japan
hayasaka@pfsl.mech.tohoku.ac.jp

Takami Yamaguchi
Department of Bioengineering and Robotics, School of Engineering
Tohoku University
Sendai 980-8579, Japan
takami@pfsl.mech.tohoku.ac.jp

INTRODUCTION

Cardiovascular diseases are the most important causes of deaths in Western as well as Eastern industrialized countries with an increase of elderly population and the change of dietary habit of candidate peoples belong to younger generations.

The most significant background condition of the cardiovascular diseases is the atherosclerosis. It causes the myocardial infarction when it occurs in the coronary artery of the heart and the various types of cerebral strokes when it affects the arteries in the brain. The atherosclerosis is not a simple disease as generally presumed. An accumulation of lipid in the arterial wall occurs where some precursory or early changes of the arterial wall cellular structure are formed under an influence of the mechanical circumstances of the arterial wall including the wall shear stress.

To determine the mechanical environments in the blood vessels, we encounter various difficulties. They are, firstly, the complex geometry of the vascular system. It is no longer a simple tubular system with a circular cross section, but it is with curves, torsions, branches, tapers, etc with individually different topological (i.e. connections of branches) structure. The vascular system differs from one person to other just like as their faces. Secondly, we always have to analyze it under unsteady conditions due to pulsating motion of the heart, the only energy source in the cardiovascular system. Thirdly, the wall of the artery is not rigid, and this imposes serious difficulty when it is combined with the unsteady flows. Fourthly, the blood, the working fluid of the cardiovascular system, is never a Newtonian fluid, since it consists of substantial volume fraction of cellular components such as the red blood cells.

All these problems are nonlinear and difficult to deal with by experimental means in the real blood flow. This is particularly true when they are to be examined in a human body. Restriction of the measurements in the real human body is very strong and the computational fluid dynamics (CFD) method is, in a sense, the only solution to analyze the blood flow phenomena.

AIM OF THE DEVELOPMENT

It is therefore necessary to establish the methods to capture and analyze the complex nature of the interactions among the blood constituents, the blood flow and the vessel wall. We have been developing an integrated system for the blood flow analysis using computational fluid mechanics based on various imaging technologies that are widely used in the clinical practice of medicine. We are developing this system for its possible use in an emergency medical diagnosis and treatments by supporting the clinical decision made by medical practitioners, providing more quantitative and predictive information.

In the course of the development, we could complete at least the first comprehensive software system that can be implemented in the real medical practice. It is expected to be the first usable system as such in the field of CFD applied to the clinical medicine. By using the currently proposed methods, we would like to show the potential of the developed system.

DEVELOPED SYSTEM

Use Case and General User Interface

As a primary use case, we postulated a scenario of a semi-emergency case of cardiovascular events such as suspected rupture of the aortic aneurysm and an acute coronary syndrome. The scenario starts with an admittance of a patient whose history is not well known but the clinical condition strongly suggest acute and urgent cardiovascular events. In such a case, some urgent examinations, including CT or MRI, are usually conducted. We assume that there is no sufficient time for computations before the clinical decision is made.

Handling of Medical Images

Volumetric representations of the clinical images should be constructed on line with imaging instruments through network connections such as DICOM formatted communications. It is necessary to handle the volumetric data reconstructed from slices of tomographic images as fast as possible to enable a user to comprehend the problem. Our system can handle those data by using a very fast volume rendering method utilizing recently available graphics facility implemented in PC class computers.

Characterization of the Structure

Our fundamental idea of designing whole system of the CFD tools is that we rely on human ability of pattern recognition in searching and characterizing structures in complex medical images. We, therefore, designed everything, including registration, segmentation, and model building to be performed in a semi-automatic manner, in which the human decision is always of a paramount value. Operators, through sophisticated interfaces, can direct how to, where to, and what to be done for necessary procedures. For example when a structure such as an aorta is segmented from the raw image, a user can direct where it starts, ends, and passes, manually so that no erroneous automatic differentiation is necessary.

CFD Model Building

The arterial systems were, as the first order approximation, represented a combined pipes separately modeled. The component pipes were connected each other by using an overset grid method in which every component shares some portion of itself with other components. Physical properties such as the velocity and pressure are exchanged between those overlapped portion of the components when the computational step proceeds to the next iterative step. We also developed an interface system to modify fine structures and surfaces of the components so that the shape of the model can be fitted onto the measured real surface of corresponding medical images.

Database of Combined Images, Models and Computed Results Indexed by the Structure

A novel indexing system was devised so that the connectivity or the skeleton representation of complex geometry of the arterial system can be semi-automatically extracted from 3D volume rendered images of cardiovascular system. Varieties of graphical representations are used as index keys of related real images, computational models, and pre-computed results using the model. Once a new urgent patient comes to the clinic, a set of MRI or CT are taken and the extracted features will be used to retrieve the set of images, models, and pre-computed results by using its skeleton as a key of database. If the patient is in urgent condition, the pre-computed results modified according to the difference of the model and the real patient can be used as the first order approximation of the blood flow estimation. Though we are fully aware of non-linearity of the flow phenomenon, it would be much better to have some means to imagine what is happening in the patient using pre-computed results rather than having nothing but just an empirical sometimes illogical imagination. By establishing this system, we will easily built a large-scale database of normal and diseased human cardiovascular system.

Visualization and Feed Back to the Clinical Medicine

Visualization program with a facility of 4D virtual reality interface is equipped in the present system. Various types of visualization are implemented so that distribution patterns of necessary physical parameters over the cardiovascular system is examined with respect to the configuration, physiological conditions and pathological states of the system to predict the outcome of the present diseases and to plan the most appropriate therapeutic measures based on the computed results.

RESULTS AND FINDINGS

We could establish a new integrated software system for the application of the computational mechanics to the cardiovascular clinical medicine. The developed system is with facilities of handling medical images, extract of basic structures, building of computational models, and comprehensive database indexed by the structure of the cardiovascular system expressed in terms of the graphical representation. The developed system is now going to be applied to the real clinical practice to accumulate the real data of patients.

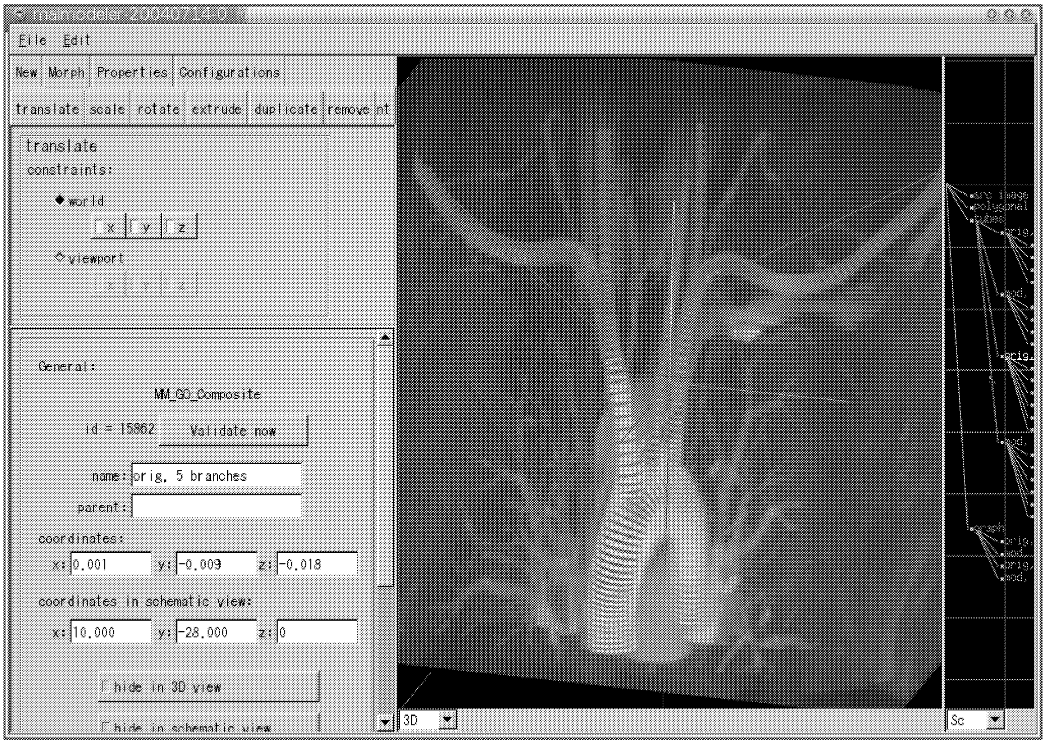

Fig. 1 A 3D volumetric representation of human aorta rendered using a set of MRI slices of images.

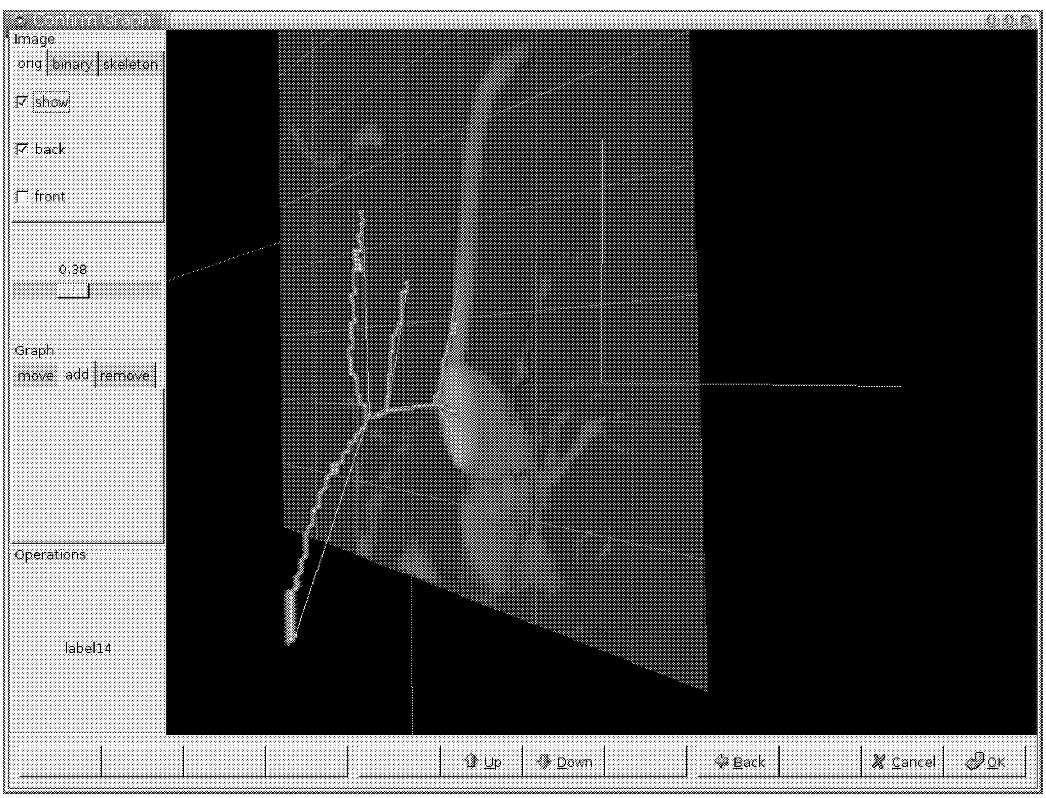

Fig. 2 An interface screen for skeletonization and extraction of topological characteristics of the aorta and its major branches.

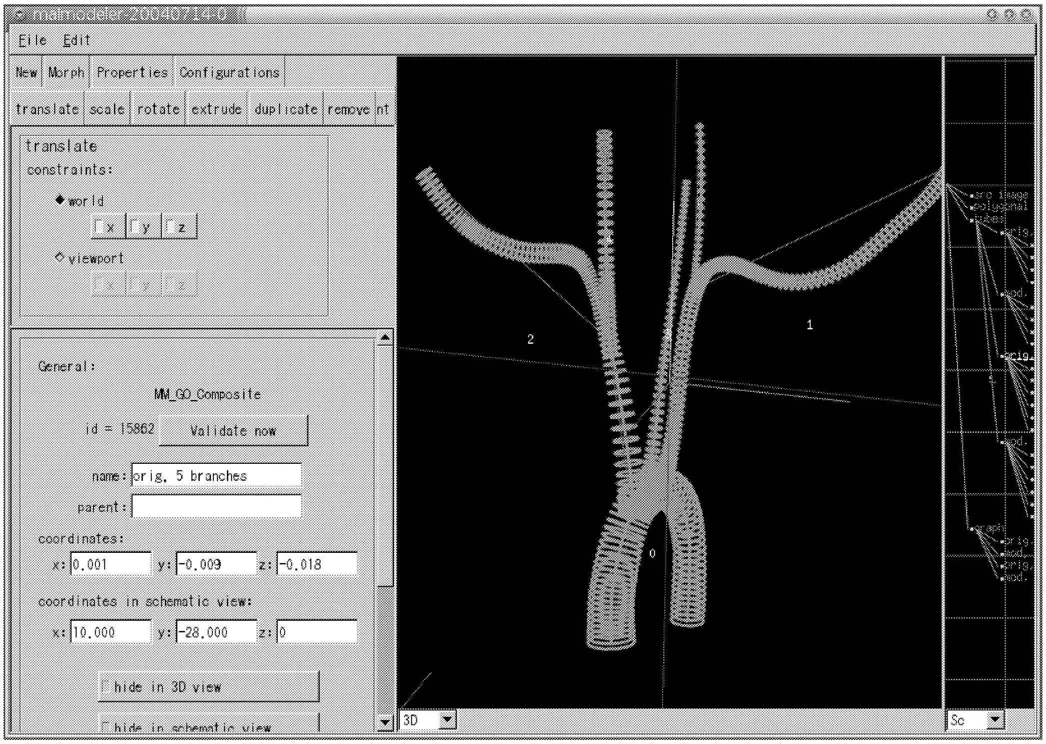

Fig. 3 An overset CFD model of the aorta and its major branches built using the skeletal representation extracted from the MRI images semi-automatically.

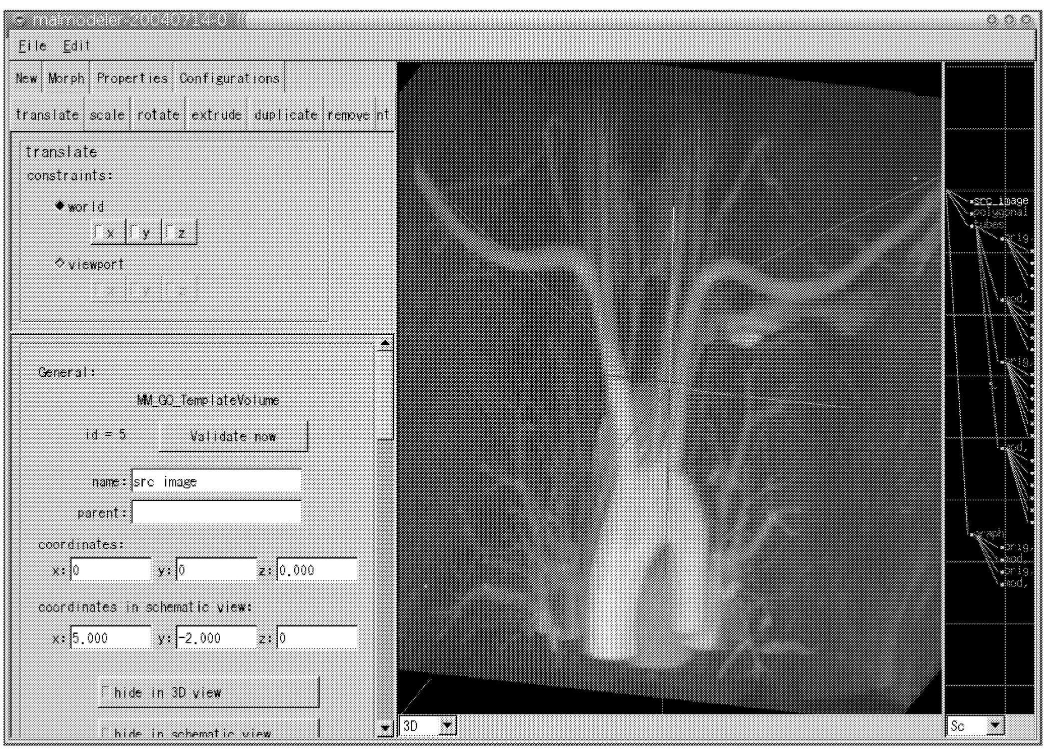

Fig. 4 The CFD model is examined against the original volumetric MRI data to adjust minute shape to the real one.