

Virtual Human Project

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ABSTRACT

This paper describes the development of a comprehensive human modeling environment, the Virtual Human, which will be used initially to model the human respiratory system for purposes of predicting pulmonary disease or injury using lung sounds. The details of the computational environment, including the development of a Virtual Human Thorax, a database for storing models, model parameters, and experimental data, and a Virtual Human web interface are outlined. Preliminary progress in developing this environment will be presented. A separate paper at the conference describes the modeling of sound generation using computational fluid dynamics and the modeling of sound propagation in the human respiratory system.

Keywords: problem solving environment, extensible markup language, physiological model, non-uniform rational B-splines, lung sounds, respiratory system

1. INTRODUCTION

The opportunity to develop a comprehensive human modeling environment has never been more opportune, given the tremendous advances in computation and the ever-increasing information revealed about the human and other animal species through various biological research efforts. In light of these circumstances, Oak Ridge National Laboratory (ORNL) has initiated the development of a human simulation tool, the Virtual Human (VH). VH will be a research/testing environment having an integrated system of biophysical and other models, data and advanced computational algorithms coupled with a computational (engineering) solid-body model of the anatomy. VH will have a World-Wide Web (web)-based interface for easy, rapid access from several points of entry. VH will serve as a platform for national and international users from governments, academia, and industry to investigate the widest range of human biological and physical responses to stimuli, be they biological, chemical, or physical. This effort goes far beyond the visualization of anatomy to incorporate physics, such as mechanical and electrical tissue properties, and biology from physiology to biochemical information, into the platform so that responses to varied stimuli can be predicted mechanistically and results viewed three-dimensionally.

The VH will provide multiple new capabilities to both military and civilian sectors. For example, VH will provide the capability of evaluating the effectiveness and safety levels for non-lethal technologies and the effectiveness of advanced clothing and armor. VH will also provide the ability to simulate training scenarios involving new equipment and methods and the capability of testing vehicle designs for safety. In conjunction with a time history of telemetered medical data, VH will provide assistance in emergency medical procedures and triage. Biomedical applications might include prosthesis design, evaluation of microgravity effects, personal medical informatics for diagnosis, patient education, and therapeutics selection. Use of the Virtual Human will minimize the need for human subjects being involved in testing and also reduce the need for animal studies.

The initial effort has focused on development of an integrated respiratory system model within the framework of the VH. The goal is to develop a VH Respiratory System (VHRS) that can be used to predict pulmonary diseases or injuries from lung sounds. First the propagation and attenuation of lung sounds in the thorax will be modeled using known sound sources and a VH thorax (VHT) we have developed. Then we will use computational fluid dynamic methods to model the generation of lung sounds. Combining the generation of lung sounds with the propagation and attenuation, we will predict injury and disease states with emphasis on pneumothorax. Auditory recordings of breath sounds available to the team will be used to validate the integrated respiratory system model. The respiratory system model, part of the VH distributed problem solving environment, will require the establishment of a computational grid, where terascale computational and informational resources will be utilized to solve for the complex vortex flow that gives rise to lung sounds.

2. BACKGROUND

ORNL has been involved in computational human modeling nearly since its inception. In the 1940s, the focus was on building mathematical phantoms capable of being used in calculations of radiation doses to workers and medical patients. The earliest computational models represented the body and its organs as homogeneous spheres. By the 1950s the geometries progressed to the rough descriptions of three shapes, the head, torso, and legs. However, with the need for more accurate calculations of radiation dose, mathematical phantoms of the human body and its organs were developed (Snyder et al. 1969, Cristy and Eckerman 1987). These phantoms used simple mathematical expressions to define the surfaces of the body and the organs. The masses of the organs were consistent with the Reference Man data (ICRP 1975). The 1970s and 1980s saw the application of these models in epidemiological studies including those of the survivors of the Hiroshima and Nagasaki bombings. In the mid-1980s, a first attempt was made to develop voxel phantoms for children using physical phantoms of various ages. Capability to use these voxel phantoms was incorporated into radiation transport codes. The techniques to construct a voxel phantom from CT images have been greatly improved over the last few years and a detailed phantom of the torso and head was constructed from the National Library of Medicine's (NLM) Visible Human (Male) image data (www.nlm.nih.gov/research/visible/visible_human.html).

Paralleling the development of mathematical phantoms, efforts were also underway to model the behavior of inhaled or ingested radionuclides within the body. These models have now evolved to include the relevant physiological and biokinetic processes and are presented as compartment models. Dosimetric considerations required that the compartments of the biokinetic models be identified with the specific organs and tissues and that a proper spatial relationship of the organs be reflected in the mathematical phantom. The latter detail is not generally required by biokinetic or pharmacokinetic models but is required by the dosimetric models.

The spatial relationships between the organs also play an important role in models used for automotive and aeronautical safety studies. But these models have not incorporated physiological function such as blood flow or biokinetic behavior. Our hope is that VH will be able to incorporate both the anatomical information and physiological and biokinetic parameters to make it possible to integrate these two modeling regimens. In addition, the mechanical, thermal and dielectric properties of human tissue and the skeletal system and the signaling characteristics of the heart, brain, and neuromuscular system must be added to make possible a reasonably complete range of modeling on the human body.

3. LUNG SOUNDS MODELING

As an example of the potential of the VHRS in medical research, the problem of lung sound changes with injury or disease could be modeled. There is a need to develop a capability to monitor and quantify lung pathological disorders from the thorax region. This need stems from the fact that patient's movements or the existence of chest wounds creates problems for locating the stethoscope. Another point of major importance is that the throat region provides an ideal place for locating the stethoscope. The key is to be able to assess from the throat region disorders such as pulmonary fibrosis, lung consolidation, etc., in the thorax region, which are generally localized to the gas-exchange region of the lung. This capability would enhance medical diagnosis for combat casualty care as well as civilian clinics. There is a need to develop an effective model of sound transmission from the lungs through the chest that would provide the needed data to develop such a capability.

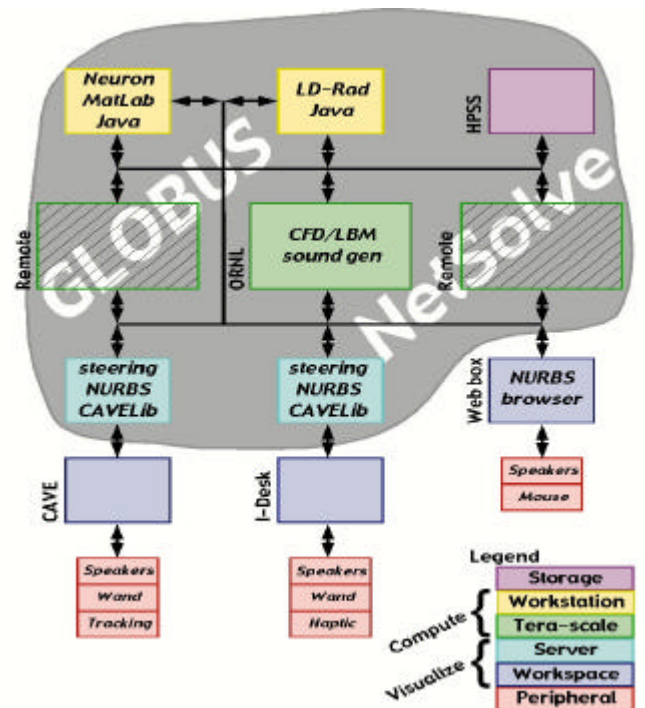
The modeling of lung sounds can be divided into two tasks that require the use of high performance computing to solve complex partial differential equations. The first task involves modeling the propagation of lung sounds in the body. The proposed approach is to model the body tissues as inhomogeneous fluids, resulting in a non-homogeneous wave equation for the acoustic pressure in the tissues. This equation derives from Lighthill's equation (reformulation of Navier-Stokes equation) for sound generation by flow after simplifying assumptions are made. The sound propagation equation requires spatially distributed information for the tissue's mass density and speed of sound, which is obtainable from the NLM's Visible Human CT scan data.

The second task involves actually modeling the generation of sound sources from the flow of air in the airways. If the entire problem were solved, computational fluid dynamics (CFD) would be needed to model sound generation due to vortices, turbulence, airway wall flutter, airway closure, mucosal lining effects, etc. for the entire lung. We will pick one or two sound generation phenomena to model in this project, but others can be added later. With the current terascale computational resources, we will only be able to model the flow in a few branching generations of airways at a time. We will then devise a method for replicating the results over a distribution of airways of the same generation to use as the sound source to the sound propagation model. Details of the lung sound modeling will be presented separately at this conference.

4. COMPUTATIONAL ENVIRONMENT

To carry out studies of lung sounds we will need to create a problem solving environment (PSE) for the Virtual Human (VH-PSE). A PSE is an all-encompassing computational environment (www.cs.purdue.edu/research/cse/pse/) which allows for problem specification, model generation, computation with computational steering, and visualization of results. The complexity of the VH-PSE will require a new way of structuring the scientific work - a paradigm change in the use of computational resources. Resources (hardware, software, instruments, databases, and people) will be collected into a *computational grid* (Figure 1), which has the ability to provide, on demand, the concentration of terascale computational and informational resources required for simulation-intensive research. Utilizing collaborative technology and the computational grid, the VH-PSE will be available over the Internet to researchers and other users throughout the world, thus allowing individual researchers to tap into a significant pool of respiratory and cardiovascular system research. Locally, the VH-PSE will have extensive, state-of-art visualization capabilities (including virtual reality) and haptic feedback devices.

Figure 1. The computational environment for VH is based on using *NetSolve*, which in turn uses GLOBUS as an underlying connectivity layer. The user accesses the VH modeling environment using a workstation or desktop computer. Jobs are then submitted to the agent-based *NetSolve* server, which looks for available resources on a computational grid of high-performance parallel computers. Results are returned to the user and displayed at the desktop using a Web-based NURBS browser. In the future we plan to display results in virtual-reality environments such as a CAVE or an I-Desk. Our plan is to connect the environment to the ORNL High-performance storage system (HPSS) to store models and experimental data.



Middleware is the main software component that unifies a given hardware and network infrastructure into a computational grid. The VH system will be implemented using a grid-programming environment called *NetSolve* (www.cs.utk.edu/netsolve/), which was developed by the University of Tennessee. It is a software environment for networked computing designed to transform disparate computers and software libraries into a unified, easy-to-access computational service. It was designed to support applications that can deliver the power of computational grids to the desktops of users without being complicated to use or difficult to deploy.

NetSolve is a natural choice for a software framework for a project based on grid computing. A major strength is its ease of use. *NetSolve* can leverage existing codes and software libraries for quick deployment on the grid, providing access to that software through widely used and familiar interfaces, such as *MATLAB* and *Mathematica*, which shield the user from the complexity of the underlying system. Even though its programming model is simple, this simplicity makes *NetSolve* modular in a way that allows for clean and effective implementations of important functionalities such as distributed data management, migration and load balancing, effective scheduling and fault-tolerance. This combination of ease of use and lightweight modularity makes it an excellent environment for prototyping new ideas and deploying new technologies for testing and experimentation in a grid environment.

Finally, the VHRS computational environment will need to have an easy means of accessibility by the user - a sophisticated graphical user interface (GUI). The interface will allow the user to select the degree of sophistication of the virtual thorax (spatial resolution, organs identified, etc.), the degree of sophistication of the physiological models, the spatial resolution of the results, the temporal range of the problem, the desired solver code, and the nature of the output to be visualized.

5. PROGRESS

A separate talk at the Aerosense 2001 Conference will deal with our progress on modeling the airway flow using computational fluid dynamics and the simulation of lung sounds. In this presentation we describe the progress made in developing a computational environment for the VH. The original goals of this phase of the Project included developing a VHT, creating a VH database architecture, and developing an extensible markup language (XML) for describing the model, model parameters, and experimental data, and creating a web interface incorporating some examples of physiological models described using this XML standard.

The VHT has been created from Visible Human data for the body surface and the major internal organs, by converting segmented organs to Non-Uniform Rational B-Spline (NURBS) surfaces. The surfaces were thence converted to a Finite-Element (FE) mesh for use in trauma simulation or to Virtual Reality Modeling Language (VRML) format for use in the web interface. A database was designed and partially implemented using XML as a model description language; information management issues such as efficient transmission of large data files (>100 MB) were explored. A prototype VH Web Interface (VHWI) was developed using Java and a number of physiological models have been incorporated into the VH-PSE. An alternative approach using a web/CORBA interface was also explored, in particular as an interface to the CFD code. Finally, CFD studies were initiated in collaboration with researchers at North Carolina State University using a parallel code developed by the University of Tennessee. These studies will be discussed in a separate presentation at this conference.

6. VIRTUAL HUMAN THORAX (VHT)

We chose to develop a virtual thorax using NURBS due to the ease with which NURBS surfaces can be modified and scaled. The concept is to create a virtual thorax by converting the Visible Human (male) data to NURBS surfaces. A NURBS scaling program (a C++ program) could be used to morph the skeleton and organs using a set of scaling rules into male phantoms of various ages and sizes. A NURBS phantom could also be animated using software such as *Maya* (from *Alias/Wavefront*) or *Lightwave* 3D (from *NewTek*) to provide avatars for medical training software and other applications.

To develop a high-resolution virtual human thorax, several steps are required. We begin by segmenting (identifying) the organs in an image (CT cross section) of the Visible Human Male. This is accomplished automatically for some organs (e.g., lungs) and skeleton, but must be done by hand for most. We then converted the output of the segmentation program to a file containing points specifying the surface of a desired organ or skeletal component. A separate set or slice of points, corresponding to each frozen CT cross-section, is created. The NURBS software (*Rhino*) reads these files for selected organs starting first with the lungs, proceeding to the heart, and so on. Due to the large number of data points involved (the surface of a typical organ such as the heart may be defined by thousands of points), only every third or fifth slice of the Visible Human frozen CT images was used.

We discovered two methods to create a NURBS surface for an organ. In the first method, the user must trace each CT slice, taking advantage of the “snap to points” capability of the *Rhino* software. The user then “lofts” the slices; i.e., creates vertical NURBS curves that connect the points on the horizontal slices. In the second method, which works well for ellipsoidal or spherical objects such as the heart, the user starts with an ellipsoid and by “pulling and tugging” makes the ellipsoid match the CT image data. Using either method, one can smooth the surface by selecting the number of control points in the horizontal and vertical directions. We found that the heart required about 100 control points and each lung about 120 control points. This creates very high-resolution, smooth surfaces of these organs and illustrates a most important advantage of using a NURBS-based representation for the various organs. Whereas the CT representation of an organ must be stored as thousands of data points in files of many megabytes in size, the corresponding NURBS representation can be achieved with only a few hundred or so data points stored in files of a few kilobytes in size.

We manually segmented and classified the liver, spleen, stomach and esophagus. The diaphragm was produced by hand-drawing a surface to fit below the lungs and heart and above the liver, spleen and stomach. The diaphragm will be needed for dynamic working models of the pulmonary system. The completed NURBS model of the torso data (the VHT) is shown in [Figure 2](#).

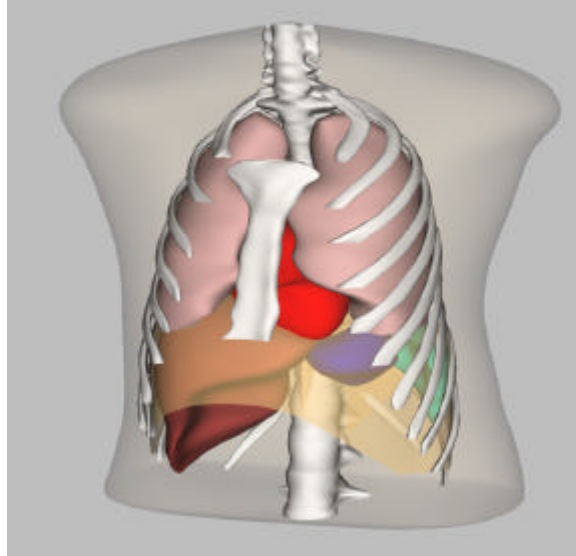


Figure 2. NURBS model of Visible Human thorax.

We consider this the primary model. This prototype NURBS model forms the basis for developing FE mesh models for trauma simulation, for animations for medical training, and for creating a scalable “Reference Man” phantom for future work in dosimetry and automobile crash testing among many other possible applications. We found that creating a NURBS surface of the spine was very difficult, given the irregularities resulting from repeated vertebrae and disk units. For purposes of the finite-element (FE) modeling, which does not have to have the most realistic looking structure, we chose to simplify the spine to a cylinder of tapered, elliptical cross sections that retained the curvature of the spine.

7. CREATING A FE MESH FROM THE NURBS VHT

An important accomplishment of human modeling will be detailed simulation of trauma effects for use in vehicle crash testing or trauma care training. This required the development of a FE model. The first step in this process is the creation of a FE mesh representation of the NURBS VHT. We accomplished this by creating an IGES standard (default) output from *Rhino*. The IGES standard file format can be read by the FE mesh generator PATRAN. We found that regularly shaped and complete solids (whose NURBS representation consisted of a single surface) such as the heart were relatively easy to mesh using an essentially uniform nodal spacing. Each lung surface, which consisted of five separate surfaces and whose inferior surface contained narrow, sharp edges, required a much higher degree of adaptive meshing (i.e., a highly non-uniform mesh with much higher resolution in the vicinity of surface irregularities).

The skeleton was easy to mesh once we simplified the shape of the spine. Finally, we meshed the “remaining tissue;” that is, all tissue not defined as lung, heart or skeleton was meshed to match the surface mesh of the heart and lung. Once the mesh was defined, appropriate material properties such as elastic moduli were assigned to the elements corresponding to the various organs, skeletal components, and remaining tissue. The completed FE mesh of the NURBS VHT (with no scaling for age or size) is shown in [Figure 3](#).

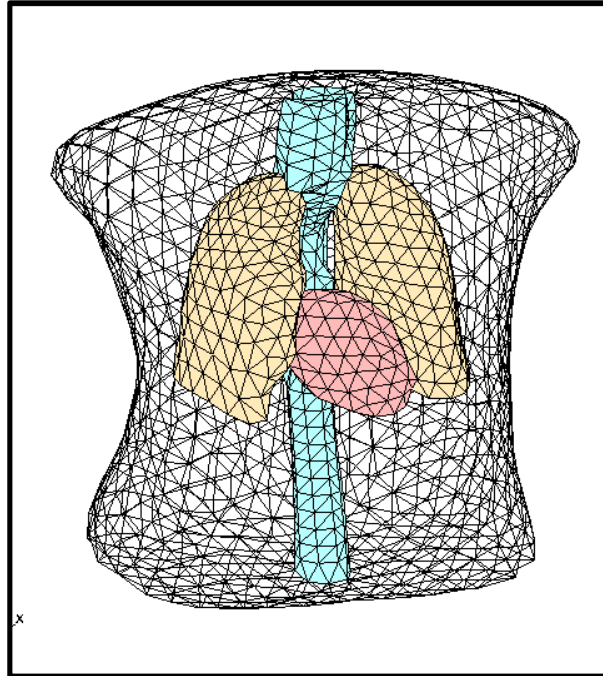


Figure 3. Finite-element mesh of the Visible Human torso.

To create animations, we exported an IGES file of the NURBS VHT and imported this into *Rhino* or into *Maya* CAD software. A VRML format output was created which allowed for animation of the organ. The VRML file of the VH torso (www.ornl.gov/virtualhuman) can be viewed using the *Netscape* or *Internet Explorer* VRML player plug-in (e.g., *Cosmo Player*). Similar methods to those described above are being applied to creating FE mesh of microCT images of lung airways for use in CFD modeling.

8. VHDB – THE VH DATABASE

The VHDB has been developed as a prototype of what might be needed to support the integration of biomedical models. VHDB can serve as a repository for information about the models, related publications, contact information, parameters and configuration information needed to run the models, specific settings used to create model output, and file location for model output. The process of designing the VHDB did not employ a formal business area analysis or information strategy planning, steps in Information Engineering (IE) that are often done for commercial relational database development projects. Because the nature of the project was evolving throughout the course of the research, the needs and requirements of the database were also evolving. Thus, an iterative approach was adopted for doing the database development that employed several techniques borrowed from different IE methodologies, adapting them to a research environment.

The conceptual analysis of the information and data needs of the VH Project involved gleaning relevant facts from team meetings, publications relating to human modeling and discussions with team members. How to identify and pass information between models and what role the database would play in that was also a part of the analysis in developing VHDB. The VH team members were asked to think of different ways the VHDB could be used. These *Use Case* scenarios were helpful in identifying flow of information into and out of the database. The Use Case studies were done in lieu of an Activity Analysis, usually done in a formal IE project. Our highest priority was to model the information and create the data structures necessary to support it. Planning for development of applications that made use of the database was a lesser priority, given the funding and scope of the Project. As the entities of the VH project were identified, we began writing a data specification document to define what characteristics or attributes we needed to track for each entity. This began as a word processing document that could serve as a strawman for discussion. That specification was the precursor to the data dictionary of the VHDB. To analyze the relationships between the different entities, we employed entity relationship diagrams (ERD).

set that are recognized by web browsers. In XML, the application builder can create any tags desired, but the application must know how to interpret the tags. There is an infrastructure in place to parse the tags (using Simple API for XML or SAX, for example) and this infrastructure can read separate files (called Document Type Definition files) that constrict the types of data allowed in the XML file. We decided to construct an XML model language for the VH. Two projects were conducted to prototype this effort. In the first project, an XML parser (JAXP, for Java XML Parser) was incorporated into the VH web interface to parse a prototype XML model configuration file. After a great deal of adjusting in the nature of this file, the construct (Figure 5) of the model XML file was arrived at.

```

<?xml version="1.0" ?>
<simulation>
  <screen width="1000" height="680">
    <panel R="255" G="255" B="255" width="1000" height="680">
      <name>Main</name>
      <description>LH-PF-1 - Left Heart 1 (Riderout)</description>
      <title>LH-PF-1 Scenario</title>
      <url xloc="0" yloc="0">http://www.ornl.gov/~rwd/image.gif</url>
      <label id="0" xloc="50" yloc="240" color="black" style="3" units="s">Simulation Time</label>
      <label id="1" xloc="210" yloc="240" color="black" style="3" units="cm3">Qlv</label>
      <label id="2" xloc="340" yloc="240" color="black" style="3" units="cm3">Qca</label>
      <label id="3" xloc="270" yloc="60" color="blue" style="2" units="mmHg">Plvm</label>
      <label id="4" xloc="570" yloc="60" color="blue" style="2" units="mmHg">Pcam</label>
      . . . . .
      <label id="19" xloc="320" yloc="125" color="black" style="1" units="">Mv</label>
      <label id="20" xloc="460" yloc="125" color="black" style="1" units="">Av</label>
    </panel>
    <panel R="215" G="235" B="255" width="200" height="400">
      <name>Server Sliders</name>
      <slider id="none">kind="server" min="0." max="1000.">Server Speed</slider>
      <slider id="none" kind="server" min="0." max="1000.">Delay</slider>
    </panel>
    <panel R="255" G="255" B="168" width="200" height="400">
      <name>Model Sliders</name>
      <slider id="11" kind="server" min="4." max="8.">Input Pressure (mmHg)</slider>
      <slider id="16" kind="server" min="50." max="150.">Beats per Minute</slider>
    </panel>
  </screen>
</simulation>

```

Figure 5. A portion of the VH model configuration file in XML form.

In the second project a simple database entry tool was created using XML and an associated DTD file. This example focused on creating an entry screen for a particular table (*itemspec*) in the VHDB. This table holds generic information such as a model variable (and associated initial condition) or a model parameter, and the units. A Java applet was written that uses a generic XML file to construct the entry screen.

10. VIRTUAL HUMAN WEB INTERFACE (VHWI)

An important part of VH will be a user interface to the physiological and anatomical models. Using a web interface would give the greatest access to the VH. To do this we decided to utilize the Java 2 and the Java Remote Method Invocation (RMI) to create a web-accessible remote modeling environment (Ward et al., 1999). Using Java as our development language will allow portability between Unix and Windows PC/NT platforms and the object-oriented development paradigm of Java will make it easy to incorporate future physiological models. Java RMI allows the client to connect to a remote server which in turn uses Java Native Interface (JNI) to connect to physiological models written in C or FORTRAN. To provide an advanced, flexible, web-based interface to VH, we developed a prototype using Java 2 which is accessible using a web-browser such as Netscape Navigator 4.5 or Internet Explorer 5. Using Java 2 allows us to take advantage of the Swing graphical user interface classes. The following physiological models have been incorporated into the VHWI: Vincent Rideout left heart model (Rideout, 1991), the simple I-131 uptake model, a Hg-vapor inhalation model developed by Leggett (Leggett, 2001 private communication), and the Roselli/Tack/Harris lung fluid transport model (Roselli et al., 1997). Each of the models could conceivably reside on separate servers. Each model is configured using an XML file that resides on the ORNL external web server. Likewise, these configuration files could reside on different remote web servers associated with the model developer. Java RMI is used to provide communication

between the user interface (a Java applet) and model executable (which could be in any programming language, C, C++, Fortran, or Java). The interface for the Rideout left-heart model (LH-PF-1), along with the VRML version of the VHT, is shown in Figure 6.

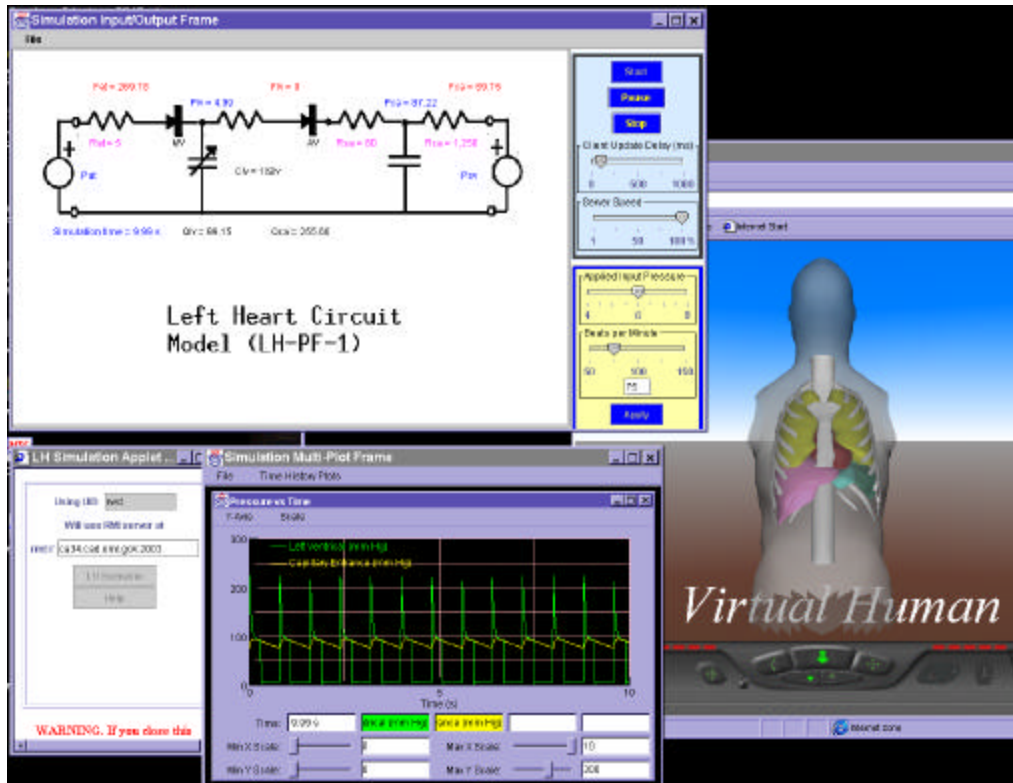


Figure 6. Virtual Human web interface for the Rideout left heart model (Rideout, 1991) including the VHT.

Java proved to be a flexible language for the development of an interface for the VH. A disadvantage of using Java is that some web browser and some platforms have not kept up to the current levels of the development of Java, requiring the use of the Java 2 plug-in to replace the Java virtual machine built into most browsers. The first time the applet is accessed, the user is required to download and install the plug-in file if it has not already been installed on the user's system. This disadvantage will disappear as the browsers are brought up to the current implementation of Java virtual machine. Advantages of using Java include the cross-platform capability and the object-oriented development paradigm, which allows us to quickly add new physiological models to the application.

The interface proved to be very flexible and provided remote access to physiological simulations in tests conducted at remote locations. Finally, we have integrated the Java user interface with the 3D anatomical models rendered using Virtual Reality Modeling Language (VRML). This allows users to click on a selected organ in the 3D anatomy and display the appropriate physiological model and corresponding simulation results.

The Java client is configured using an XML configuration file specific to the model selected. The model executable code resides on the server. The Java simulation manager on the server reads the same configuration file to construct the input (initial conditions, start and end times, time step, etc.) for the model simulation. An unusual feature of the VHUI is the ability to control the simulation from the client using selected parameters. The user selects the parameters that are to be allowed to vary prior to the start of the simulation. These will then have a slider bar that will allow modification over a user-specified range. As the simulation proceeds the user can select to modify these at any time. The modified value is sent from the client to the server and the simulation responds nearly instantaneously. When the connection is slow, latency times will affect the response of the simulation to changes in the modifiable parameters. However, this design will give students and others a very good way to observe the affect of changes of parameters on model outcomes.

NetSolve is being integrated into the VH-PSE to harness parallel computers over a widely distributed network to compute

the computational flow through the lung airways. *NetSolve* is being installed on the high-performance computers at ORNL that will be connected together with other computer clusters at the University of Tennessee to provide a unique, robust computational environment for these complex computations. Results will be returned to the VHVI to be visualized at the user's desktop. In some cases results will be visualized using the 3D, virtual reality CAVE recently located at ORNL. This capability will give researchers the ability to be "inside" the airway to observe the airflow up close.

11. CONCLUSIONS

Preliminary development of a VH-PSE has been accomplished including the design of a VH database (VHDB) that will store models, model parameters and experimental data, and the development of a web interface (VHVI). In addition, a VH XML standard for describing models and data has been prototyped and a number of physiological models have been incorporated into the VH-PSE (see <http://www.ornl.gov/virtualhuman>). The grid-programming environment *NetSolve* will provide connectivity to high-performance parallel computers and data storage. Work is progressing in developing three-dimensional models of the human thorax (VHT) and of FE models of the airways which will be used in sound generation and propagation modeling in support of studies to predict, using models, the nature of lung sounds resulting from pulmonary disease and injury. Future work will involve detailed CFD modeling of smaller airways and propagation of sound through the VHT with visualization of the results in the VH-PSE described here.

12. ACKNOWLEDGMENTS

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