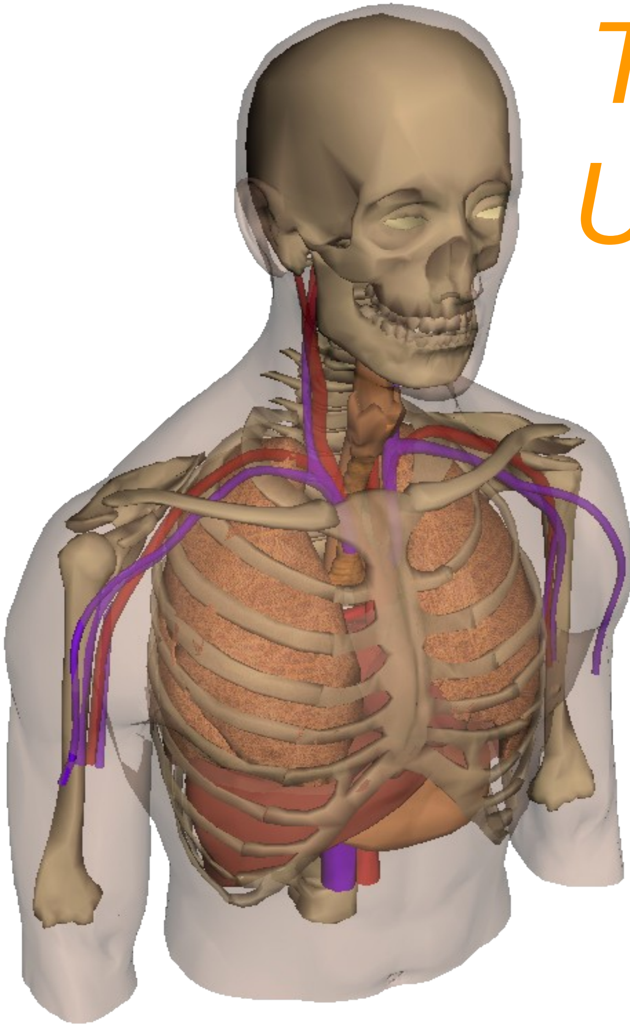
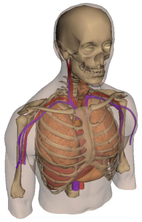


# The Digital Human: Using Computers to Improve Health

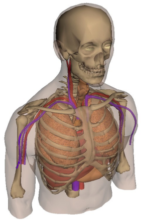
Bill Lorensen
GE Global Research
Niskayuna, NY
lorensen@crd.ge.com

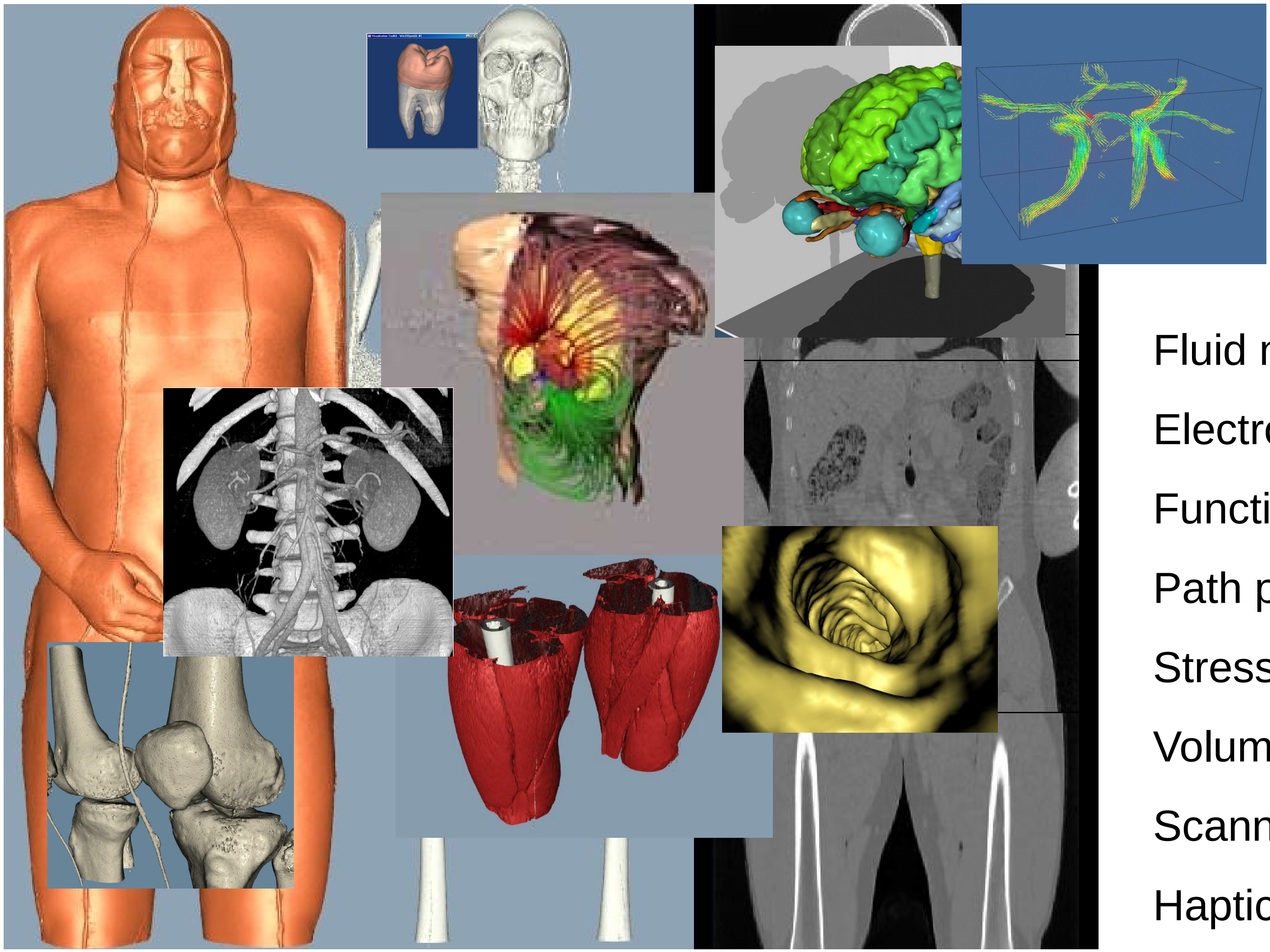


# *The Vision*

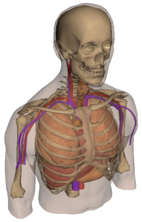
Build a clear and accurate simulation of the human body starting with molecules and proteins, progressing to cells, tissues and organs, and finally the entire human anatomic and physiological system

# *The Digital Human - Beyond Pictures*





- Fluid mechanics/dynamics
- Electro-mechanical systems
- Functional imaging
- Path planning
- Stress analysis
- Volume modeling/rendering
- Scanner physics
- Haptics

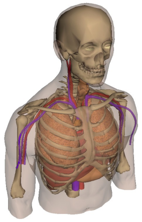


# In Ten Years, The Body Double

***The Body Double***

a *patient specific model that serves as a repository for diagnostic, pathologic and clinical information*

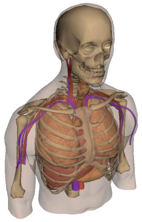
- Predictive modeling of specific biological systems
- Synthesis of diagnostic imaging, modeling and simulation with real-time therapeutics
- Validated and accurate simulations of major organs and organ systems
- High fidelity medical simulation for training and accreditation



# *Why Now?*

State-of-the-art is improving rapidly

- Experimental and sensor data are ready to support complex simulations
- Information science and hardware advances are ready to make interoperable frameworks a reality
- Numerous non-interoperable approaches underway, but flexibility remains to interface these efforts

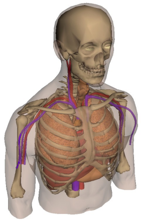


# *What will it take in resources?*

- The problem is too large for one institution
- An ad-hoc consortium of industry, academia and government met in the summer of 2000 to establish feasibility and to assess interest
- The group has met several times to refine strategy and to define a technical approach

*"Immediate results can be expected from simulations already being sponsored by the NIH and other agencies, it is likely that a compete first draft of the Digital Human will require ten years and over a billion dollars.",*

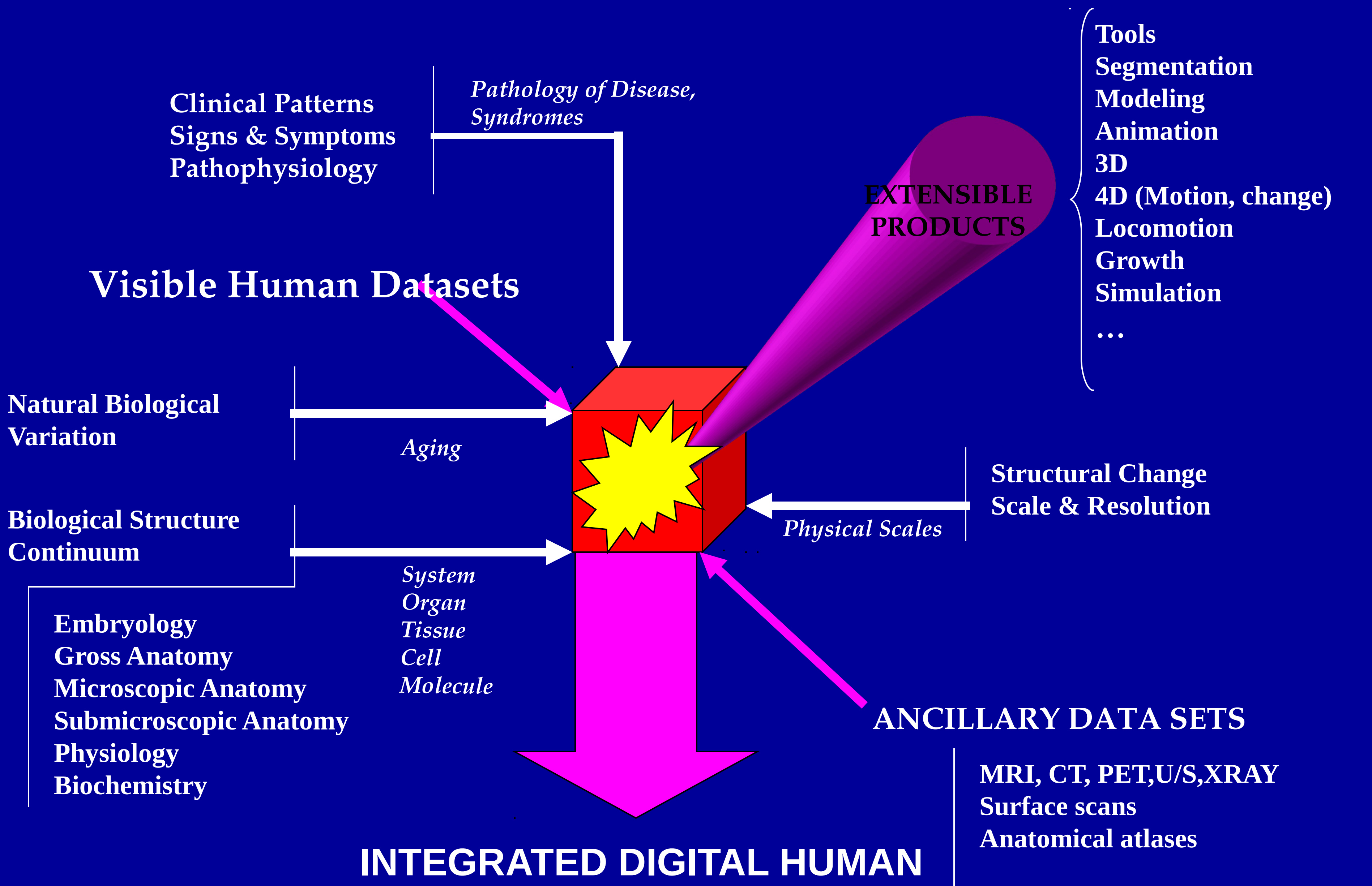
Digital Human Consortium White Paper, August, 2000



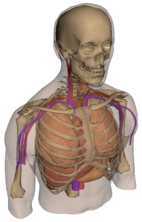
# *Technical Objectives*

- Model and simulate all relevant physical scales of the human
- Simulate all relevant time scales and stages of development
- Allow collaborative, worldwide development and sharing
- Facilitate integration into commercial products, medical education and physician training

# Cornerstone Elements of the Digital Human*

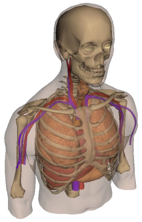



* From the Digital Human Consortium Workshop, July 23-24, 2001, Bethesda, MD



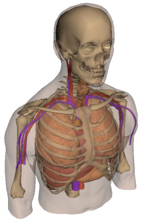
# *Modeling of Biological Systems is Difficult*

- Many physical scales may be active and important
- Dynamic interaction — continuous motion and change in components (mechanical, electrical, chemical)
- Highly non-linear, large deformations, history modifies response
- Massively parallel systems with hierarchical signaling/control
- Few rigid, static surfaces; freely changing interfaces
- Enormous diversity between individuals
- All biological objects evolved from others and inherit/conserve many characteristics
- Vast amount remains unknown — even fundamentals



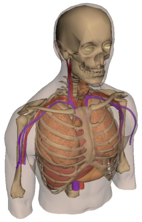
# *Grand Challenges in Biomedical Simulation*

- Great progress already for many body systems
- Multiple processes (enzyme kinetics, heart action, circulatory physiology, gait, growth, …)
- Multiple timescales ($10^{-12}$ sec molecule events, $10^{-3}$ sec force display, $10^{-1}$ sec graphics, sec→… →decade prognosis)
- Multiple methods (finite element, computational fluid dynamics, compartment models, multi-body mechanics, particle flow, Monte Carlo, …)
- Disjoint funding, communication, journals, conferences, etc.
- Model interaction for different scales or organs is rare
- Interaction of real events at different scales or organs can be critical for the human involved (e.g. heart attack)
- Lack of patient specific models



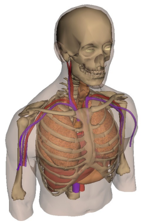
# *Long Range Benefits*

- Improve the Practice of Medicine
  - Design and test more accurate medical devices and procedures
  - Help doctors and nurses communicate with patients about health and disease
  - Reduce medical errors
  - Provide a “body-double” for each patient, to personalize diagnosis and therapy
- Simulated human surrogates to improve the safety of cars, aircraft and other vehicles, and for environmental exposure



# Short Term – 1 to 5 years

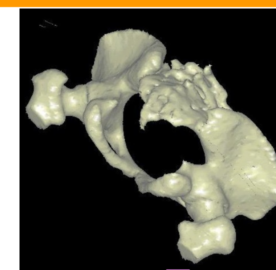
- Couple physical models of the lung to pulmonary performance
- Bone and Joint Modeling, both static and dynamic
- Systems modeling, e.g. circulatory, central nervous system
- Static fluid analysis for patient-specific arterial flow
- Software frameworks for interoperability across disciplines

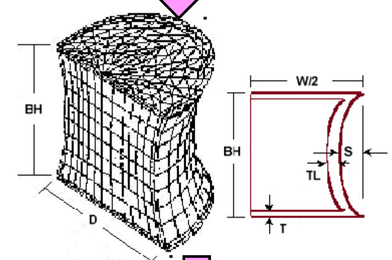


# Bone and Joint Modeling

Volume data

3D model of the part

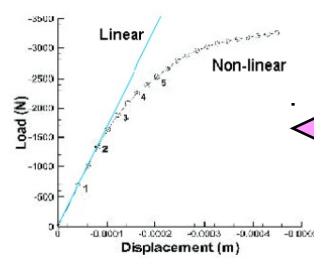




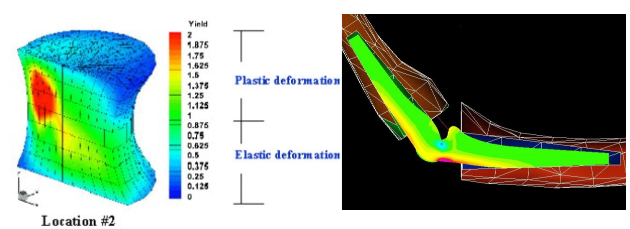

- Generate 3D models of patient from CT data
- Perform stress and load carrying analysis of bones
- Predict motions that can accelerate fracture growth in the bones
- Rapidly prototype matched joints or replacement bones for an individual

Service & recurring earnings

New Scanner Orders

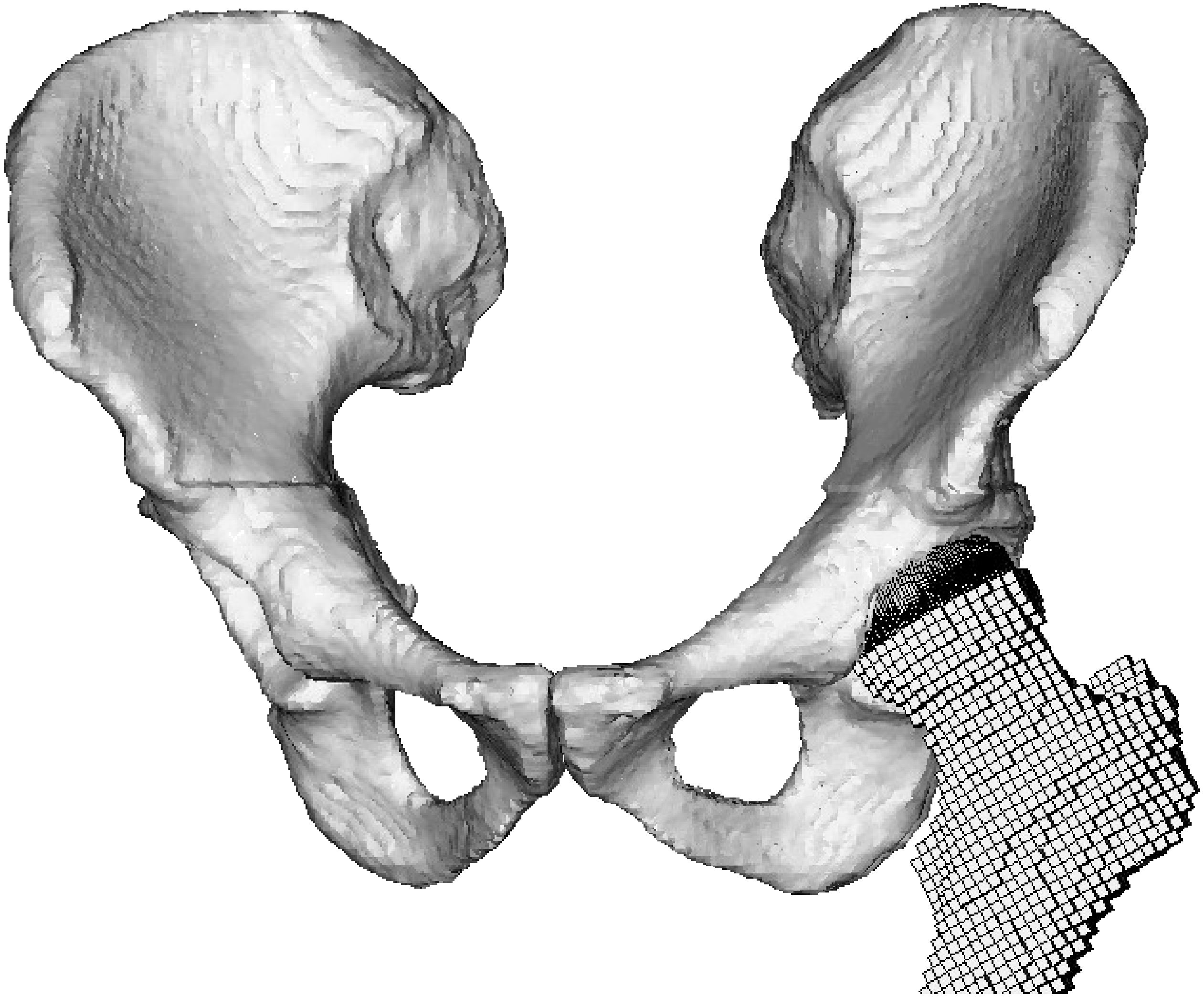



Load carrying analysis

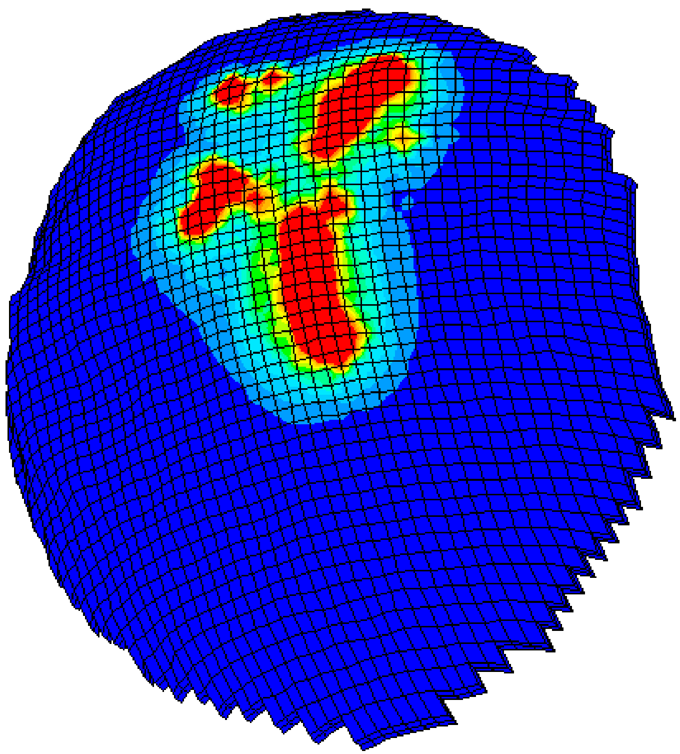


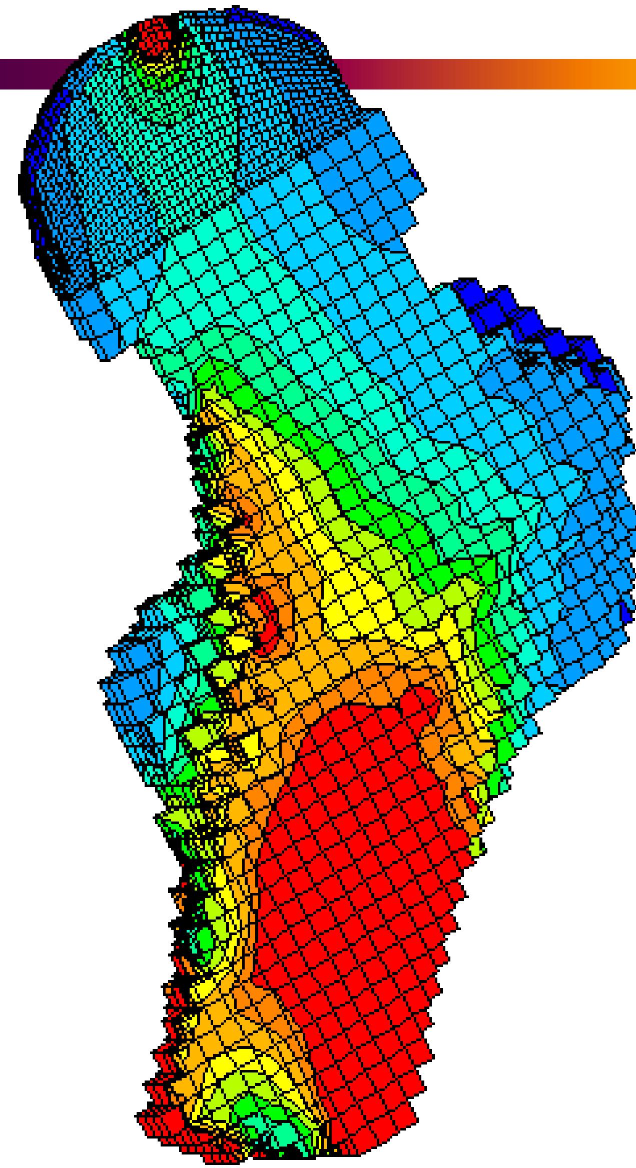

Parametric modeling & Stress analysis of human part

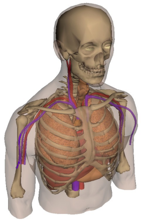
# Complete Contact Model



# Resultant Stress Contours

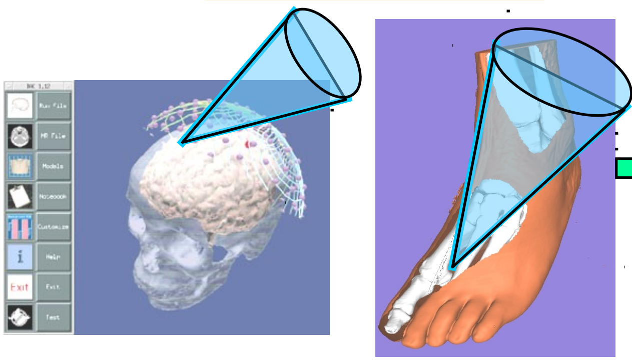




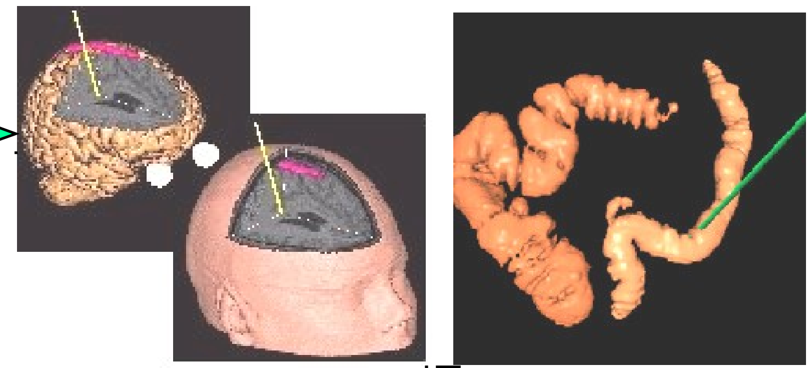


# *Organ accessibility / Surgical simulation*

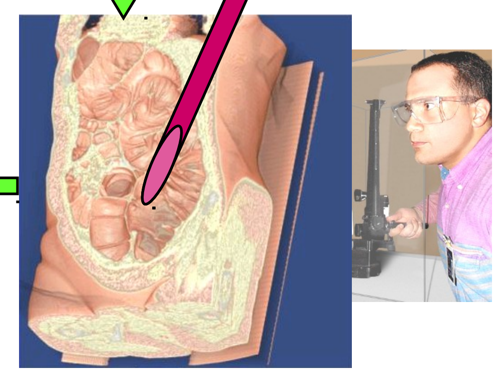
Configuration space



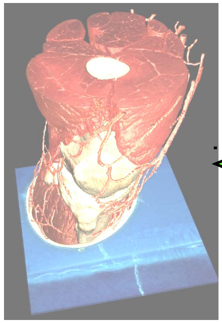
Endoscopy applications



- Determine configuration space of internal organs from the digital model
  - Endoscopy and surgical motion planning
- Surgical simulation and training
  - Mechanics of soft tissue deformation
  - Real-time haptic rendering



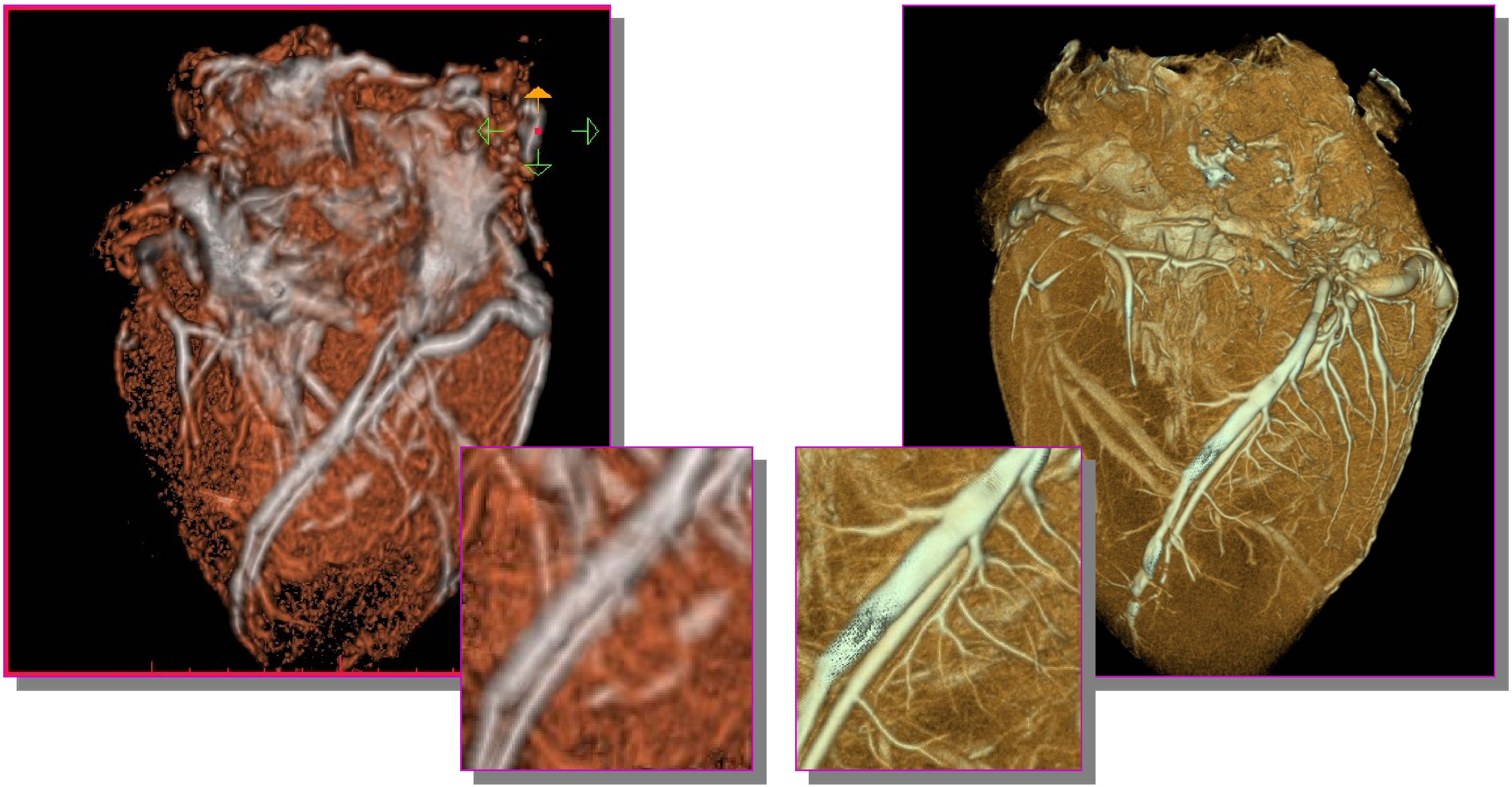
Training/Rehearsal

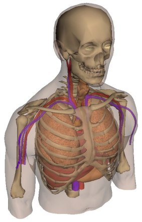


Real-time soft tissue incision/deformation modeling

Economies of scope for other commercial opportunites

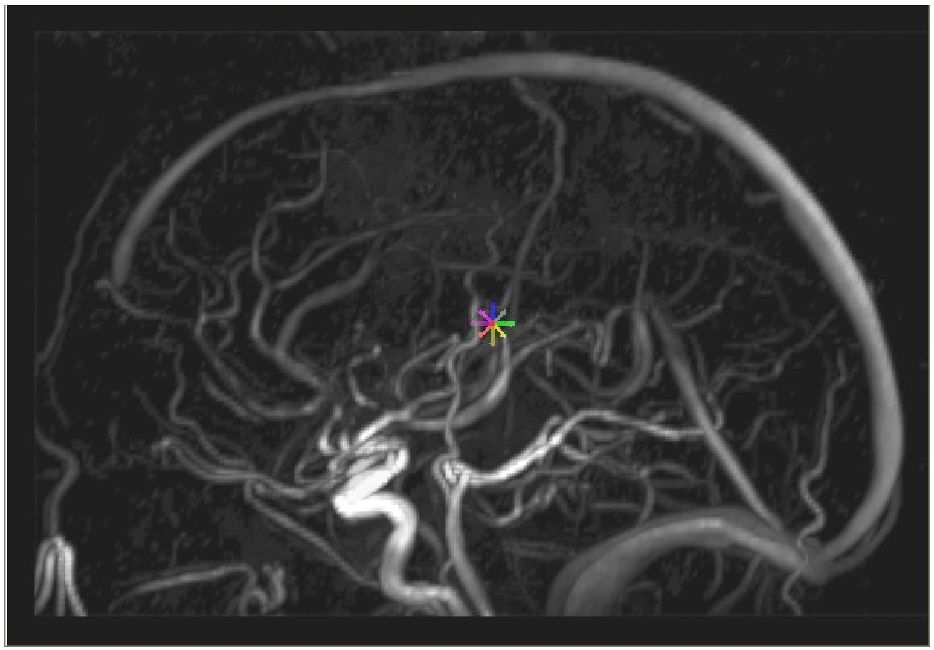
# *High Resolution Imaging*



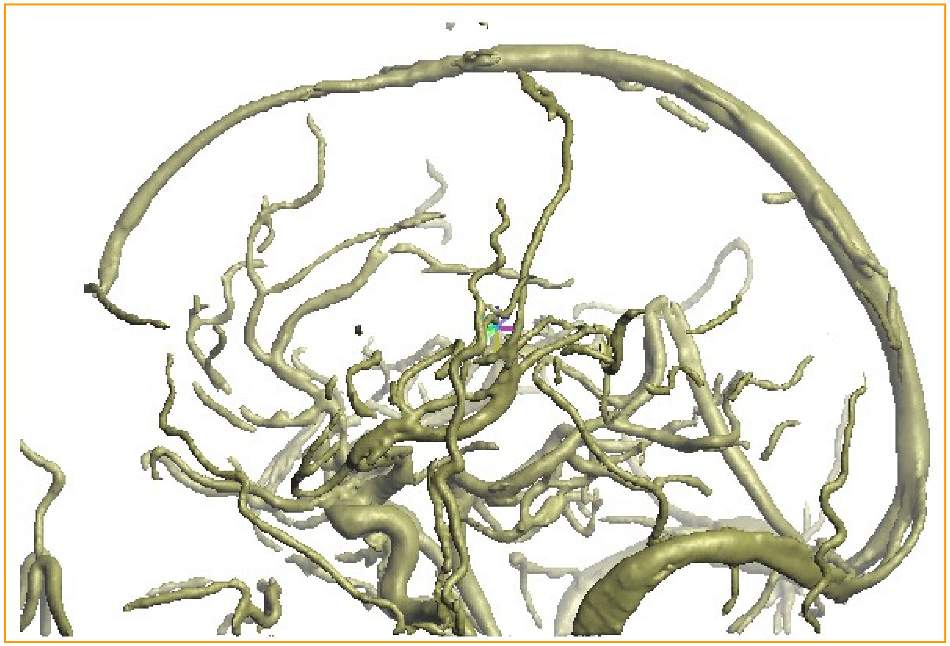


# *Applications*

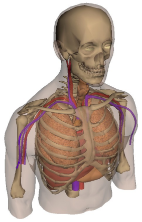
Magnetic Resonance Angiography



Maximum Intensity Projection

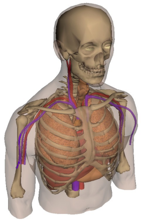


Segmentation result



# *Long Term – 5 to 10 years*

- Patient specific dynamics of the heart
- Patient specific subsystem models (CNS, circulatory)
- Cell to tissue to organ models
- Human growth and development models
- Systems engineering of the complete Digital Human

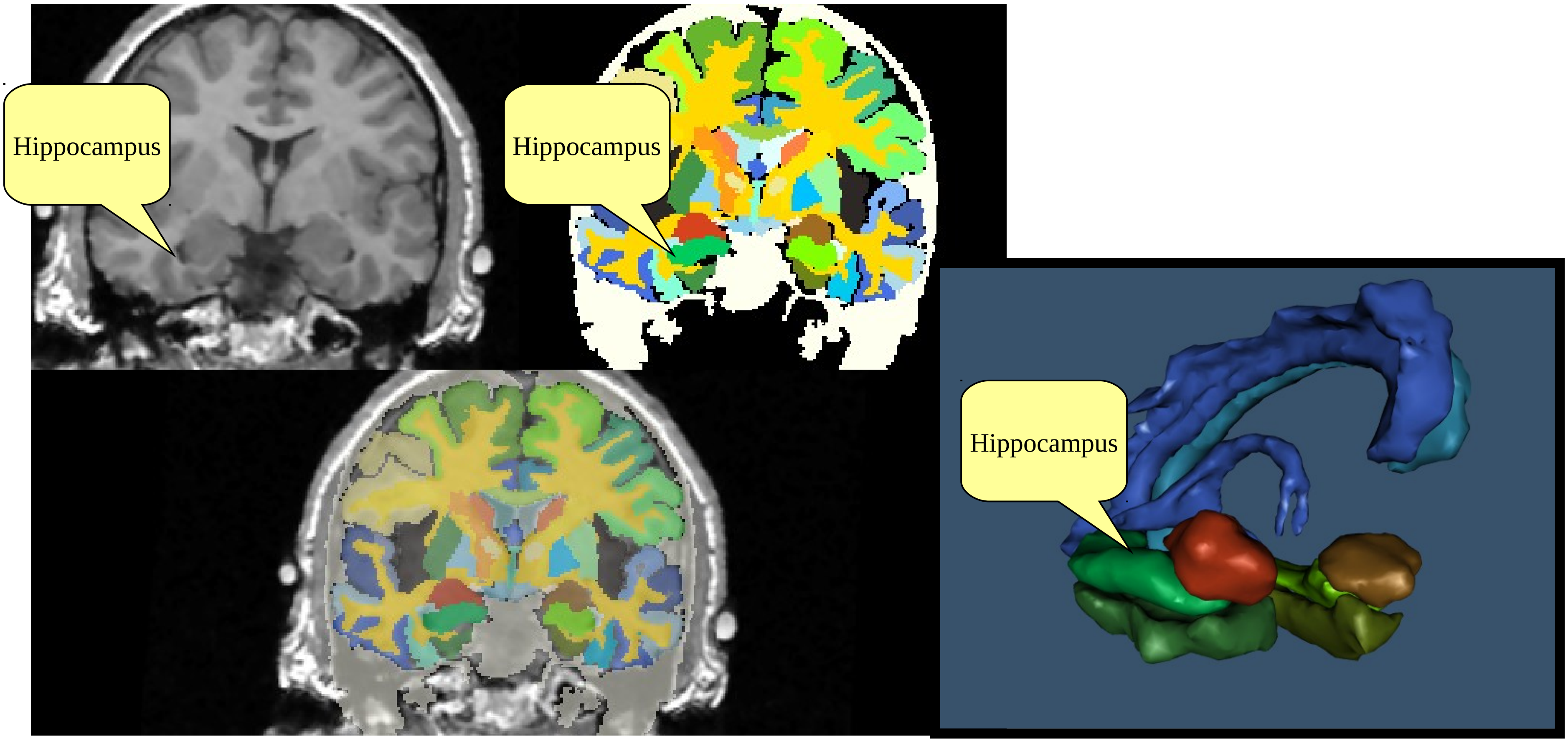


# Other Applications

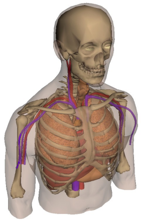
- Patient specific scanning protocols simulated on the Body Double
- Pulmonary models for chronic obstructive pulmonary disease (COPD)
- Individualized drug therapy
- Military
  - Simulate the effect of weapons and radiation on models of soldiers
- Automotive
  - Crash tests, ergonomics
- Forensics
  - Regenerate portions of human from the skeletal remains
  - Digital autopsy
- Commercial
  - Market applications with the state of the art scanning hardware

# MRI 3D Volumetrics

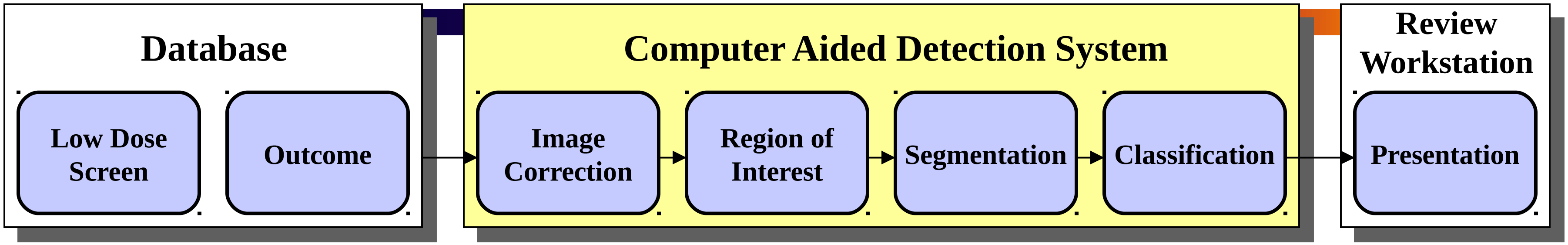
*"A discriminant function analysis demonstrated that a linear combination of the volumes of the hippocampus and the temporal horn of the lateral ventricles differentiated 100% of the patients and controls from one another."*[1]

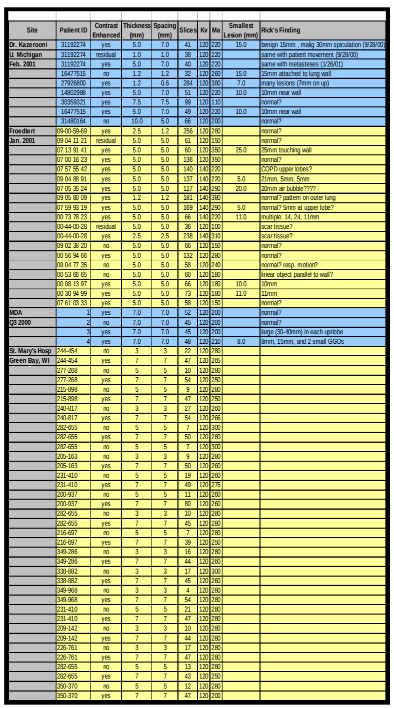



Killiany, et. Al., Temporal Lobe Regions on Magnetic Resonance Imaging Identify Patients with Early Alzheimer's Disease, Arch Neurol 50:949-954, 1993

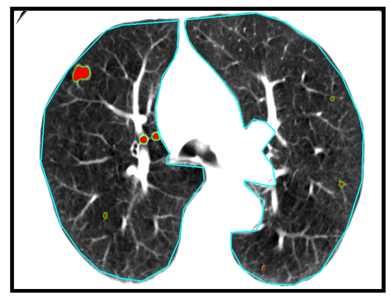


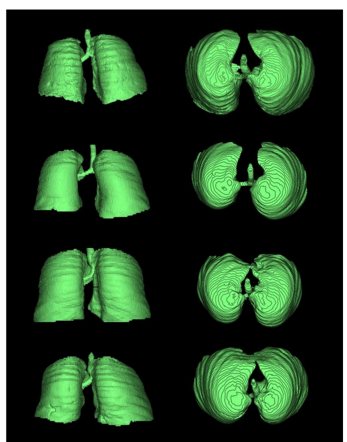
# Image Analysis

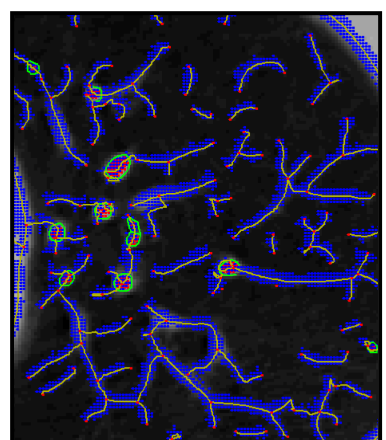


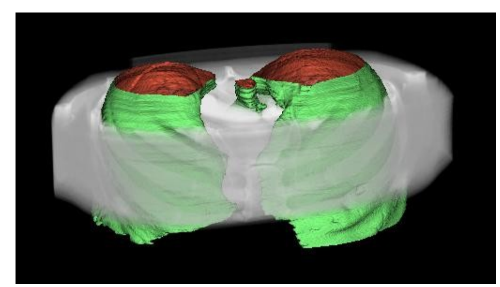



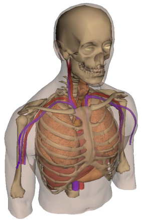
| Site | Patient ID | Contrast Enhanced | Thickness (mm) | Spacing (mm) | Slices | Kv | Ma | Smallest Lesion (mm) | Rick's Finding |
|---|---|---|---|---|---|---|---|---|---|
| Dr. Kazerooni | 31192274 | yes | 5.0 | 7.0 | 41 | 120 | 220 | 15.0 | benign 15mm , malig 30mm spiculation (9/28/00) |
| U. Michigan | 31192274 | residual | 1.0 | 1.0 | 38 | 120 | 220 | | same with patient movement (9/28/00) |
| Feb. 2001 | 31192274 | yes | 5.0 | 7.0 | 40 | 120 | 220 | | same with metasteses (1/26/01) |
| | 16477515 | no | 1.2 | 1.2 | 32 | 120 | 260 | 15.0 | 15mm attached to lung wall |
| | 27926800 | yes | 1.2 | 0.6 | 284 | 120 | 380 | 7.0 | many lesions (7mm on up) |
| | 14802988 | yes | 5.0 | 7.0 | 51 | 120 | 220 | 10.0 | 10mm near wall |
| | 30359321 | yes | 7.5 | 7.5 | 99 | 120 | 110 | | normal? |
| | 16477515 | yes | 5.0 | 7.0 | 49 | 120 | 220 | 10.0 | 10mm near wall |
| | 31480164 | no | 10.0 | 5.0 | 66 | 120 | 200 | | normal? |
| Froedtert | 09-00-59-69 | yes | 2.5 | 1.2 | 256 | 120 | 280 | | normal? |
| Jan. 2001 | 09 04 11 21 | residual | 5.0 | 5.0 | 61 | 120 | 150 | | normal? |
| | 07 13 91 41 | yes | 5.0 | 5.0 | 60 | 120 | 350 | 25.0 | 25mm touching wall |
| | 07 00 16 23 | yes | 5.0 | 5.0 | 136 | 120 | 350 | | normal? |
| | 07 57 55 42 | yes | 5.0 | 5.0 | 140 | 140 | 220 | | COPD upper lobes? |
| | 09 04 88 91 | yes | 5.0 | 5.0 | 137 | 140 | 220 | 5.0 | 21mm, 5mm, 5mm |
| | 07 05 35 24 | yes | 5.0 | 5.0 | 117 | 140 | 290 | 20.0 | 20mm air bubble???? |
| | 09 05 80 09 | yes | 1.2 | 1.2 | 181 | 140 | 380 | | normal? pattern on outer lung |
| | 07 59 93 19 | yes | 5.0 | 5.0 | 169 | 140 | 290 | 5.0 | normal? 5mm at upper lobe? |
| | 00 73 78 23 | yes | 5.0 | 5.0 | 66 | 140 | 220 | 11.0 | multiple: 14, 24, 11mm |
| | 00-44-00-28 | residual | 5.0 | 5.0 | 36 | 120 | 100 | | scar tissue? |
| | 00-44-00-28 | yes | 2.5 | 2.5 | 238 | 140 | 310 | | scar tissue? |
| | 09 02 38 20 | no | 5.0 | 5.0 | 66 | 120 | 150 | | normal? |
| | 00 56 94 66 | yes | 5.0 | 5.0 | 132 | 120 | 280 | | normal? |
| | 09 04 77 35 | no | 5.0 | 5.0 | 58 | 120 | 240 | | normal? resp. motion? |
| | 00 53 66 65 | no | 5.0 | 5.0 | 60 | 120 | 180 | | linear object parallel to wall? |
| | 00 08 13 97 | yes | 5.0 | 5.0 | 66 | 120 | 180 | 10.0 | 10mm |
| | 00 30 94 99 | yes | 5.0 | 5.0 | 73 | 120 | 180 | 11.0 | 11mm |
| | 07 61 03 33 | yes | 5.0 | 5.0 | 58 | 120 | 150 | | normal? |
| MDA | 1 | yes | 7.0 | 7.0 | 52 | 120 | 200 | | normal? |
| Q3 2000 | 2 | no | 7.0 | 7.0 | 45 | 120 | 200 | | normal? |
| | 3 | yes | 7.0 | 7.0 | 45 | 120 | 200 | | large (30-40mm) in each uprlobe |
| | 4 | yes | 7.0 | 7.0 | 48 | 120 | 210 | 8.0 | 8mm, 15mm, and 2 small GGOs |
| St. Mary's Hosp | 244-454 | no | 3 | 3 | 22 | 120 | 280 | | |
| Green Bay, WI | 244-454 | yes | 7 | 7 | 47 | 120 | 265 | | |
| | 277-268 | no | 5 | 5 | 10 | 120 | 280 | | |
| | 277-268 | yes | 7 | 7 | 54 | 120 | 250 | | |
| | 215-898 | no | 5 | 5 | 9 | 120 | 280 | | |
| | 215-898 | yes | 7 | 7 | 47 | 120 | 250 | | |
| | 240-817 | no | 3 | 3 | 27 | 120 | 260 | | |
| | 240-817 | yes | 7 | 7 | 54 | 120 | 266 | | |
| | 282-655 | no | 5 | 5 | 7 | 120 | 300 | | |
| | 282-655 | yes | 7 | 7 | 50 | 120 | 280 | | |
| | 282-655 | no | 5 | 5 | 7 | 120 | 300 | | |
| | 205-163 | no | 3 | 3 | 9 | 120 | 280 | | |
| | 205-163 | yes | 7 | 7 | 50 | 120 | 260 | | |
| | 231-410 | no | 5 | 5 | 19 | 120 | 260 | | |
| | 231-410 | yes | 7 | 7 | 49 | 120 | 275 | | |
| | 200-937 | no | 5 | 5 | 11 | 120 | 260 | | |
| | 200-937 | yes | 7 | 7 | 80 | 120 | 260 | | |
| | 282-655 | no | 3 | 3 | 10 | 120 | 280 | | |
| | 282-655 | yes | 7 | 7 | 45 | 120 | 280 | | |
| | 216-697 | no | 5 | 5 | 7 | 120 | 280 | | |
| | 216-697 | yes | 7 | 7 | 39 | 120 | 250 | | |
| | 349-286 | no | 3 | 3 | 16 | 120 | 280 | | |
| | 349-286 | yes | 7 | 7 | 44 | 120 | 260 | | |
| | 338-882 | no | 3 | 3 | 17 | 120 | 300 | | |
| | 338-882 | yes | 7 | 7 | 45 | 120 | 260 | | |
| | 349-968 | no | 3 | 3 | 4 | 120 | 280 | | |
| | 349-968 | yes | 7 | 7 | 54 | 120 | 280 | | |
| | 231-410 | no | 5 | 5 | 21 | 120 | 280 | | |
| | 231-410 | yes | 7 | 7 | 47 | 120 | 280 | | |
| | 209-142 | no | 3 | 3 | 10 | 120 | 280 | | |
| | 209-142 | yes | 7 | 7 | 44 | 120 | 280 | | |
| | 226-761 | no | 3 | 3 | 17 | 120 | 280 | | |
| | 226-761 | yes | 7 | 7 | 47 | 120 | 280 | | |
| | 282-655 | no | 5 | 5 | 13 | 120 | 280 | | |
| | 282-655 | yes | 7 | 7 | 43 | 120 | 250 | | |
| | 350-370 | no | 5 | 5 | 12 | 120 | 280 | | |
| | 350-370 | yes | 7 | 7 | 47 | 120 | 200 | | |



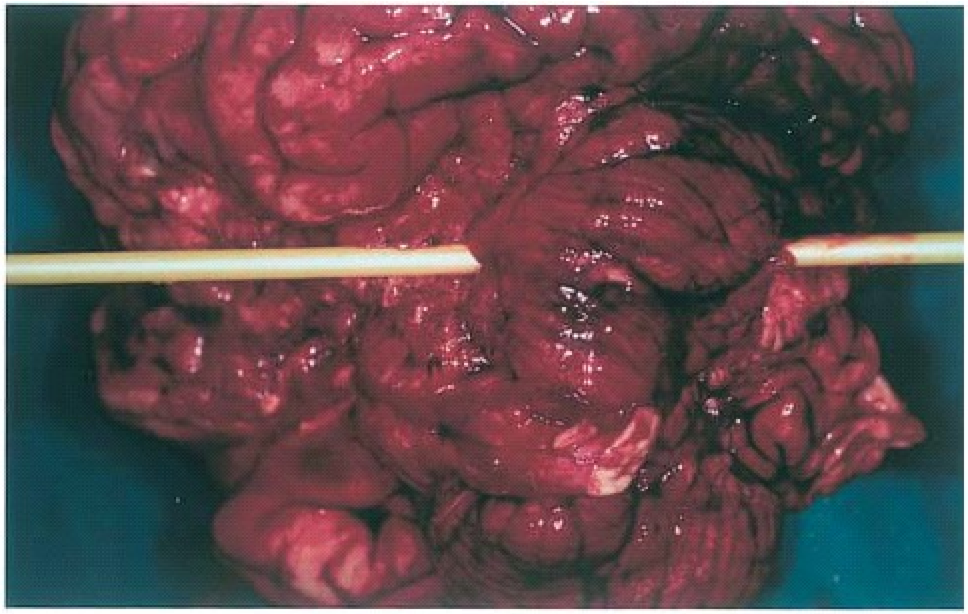








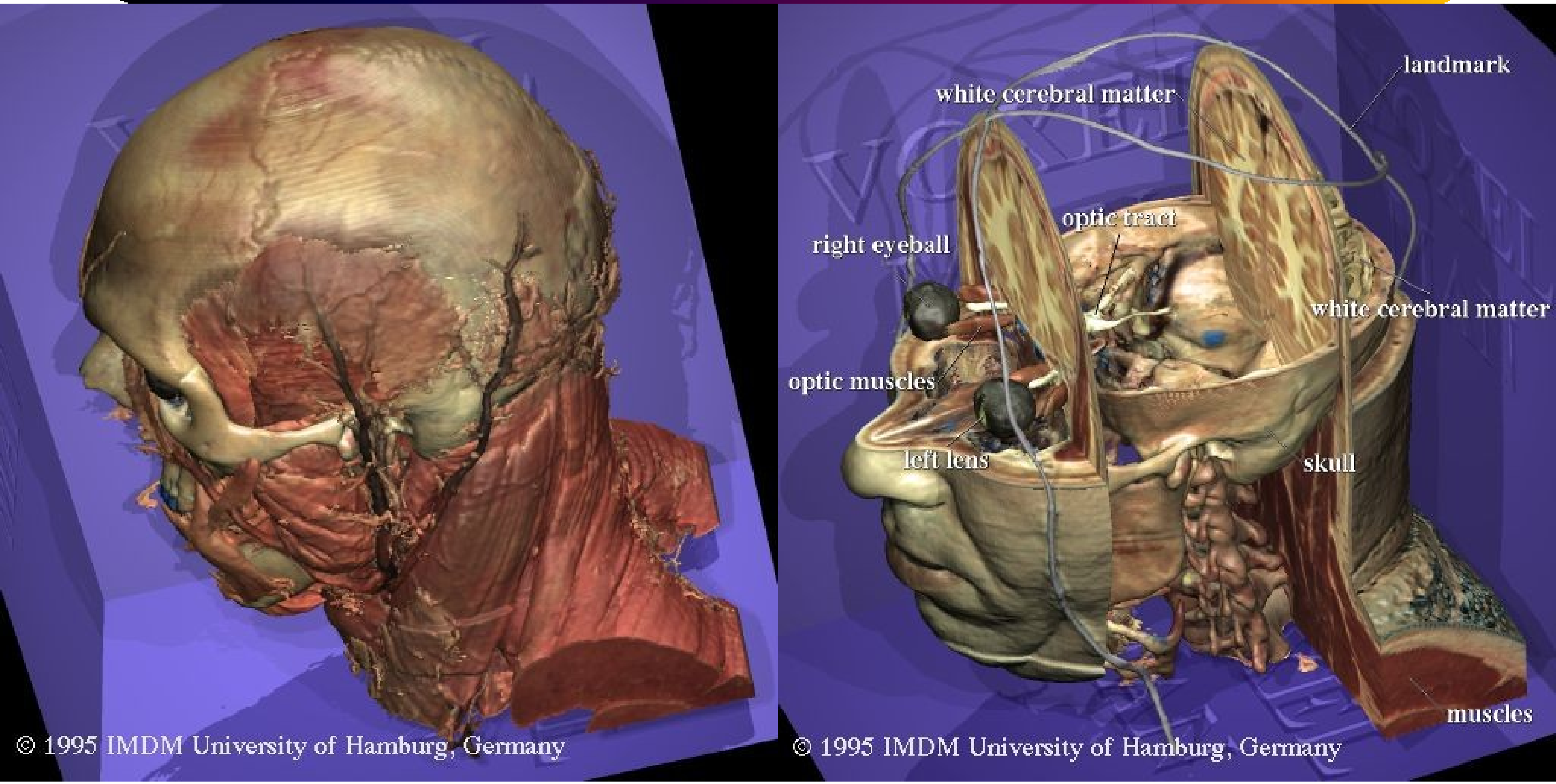
# *Virtual Autopsy*

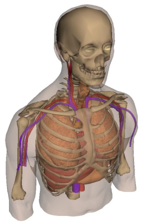
Virtopsy, a New Imaging Horizon in Forensic Pathology: Virtual Autopsy by Postmortem Multislice Computed Tomography (MSCT) and Magnetic Resonance Imaging (MRI)—a Feasibility Study*

*Michael J. Thali, et. al. J Forensic Sci*, Mar. 2003, Vol. 48, No. 2

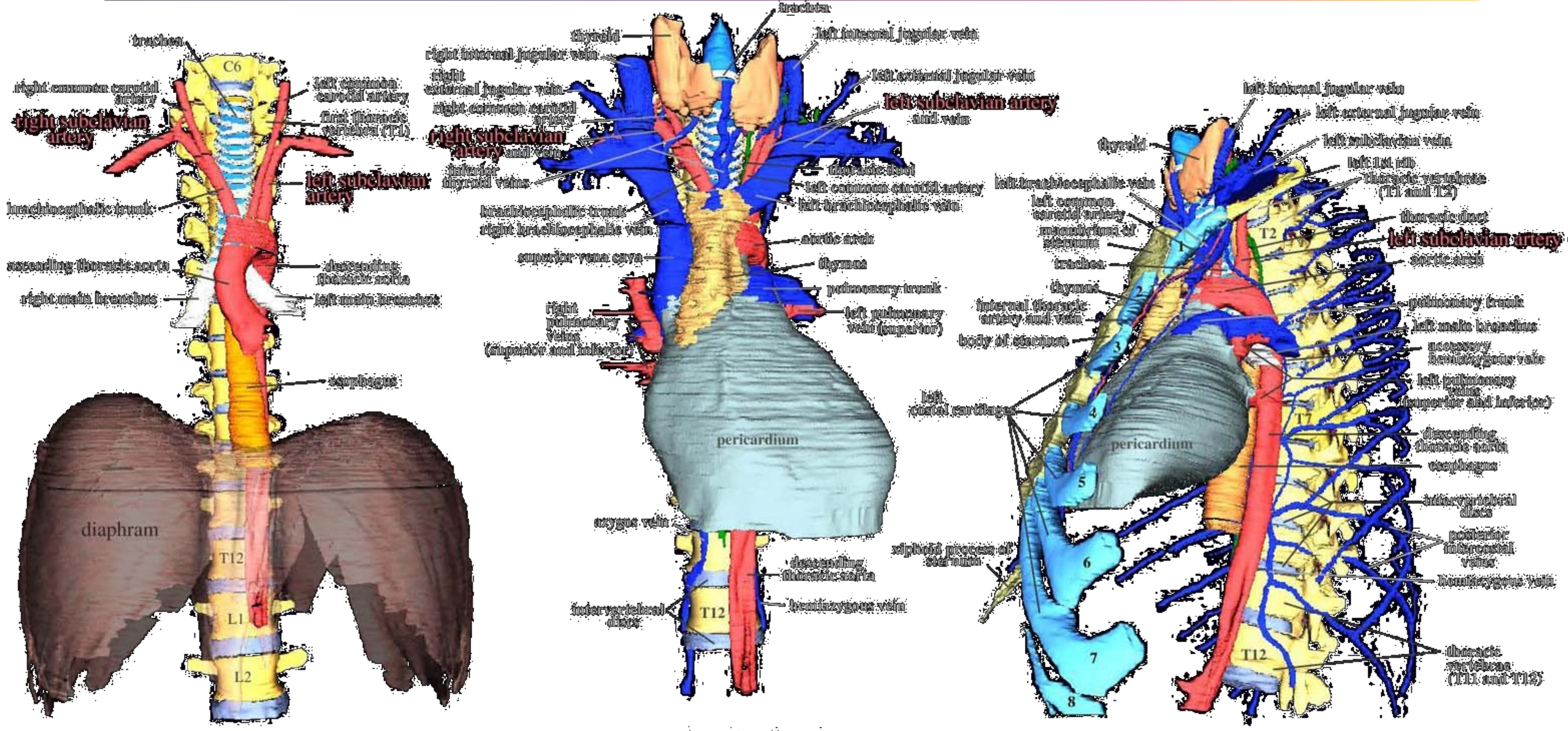
# Digital Atlases




Provided by K, Hoehne, Univ of Hamburg



# High Resolution Atlases Derived from Imaging

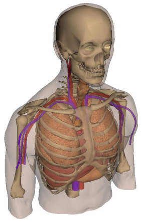



Anterior view of posterior mediastinum with transparent diaphragm

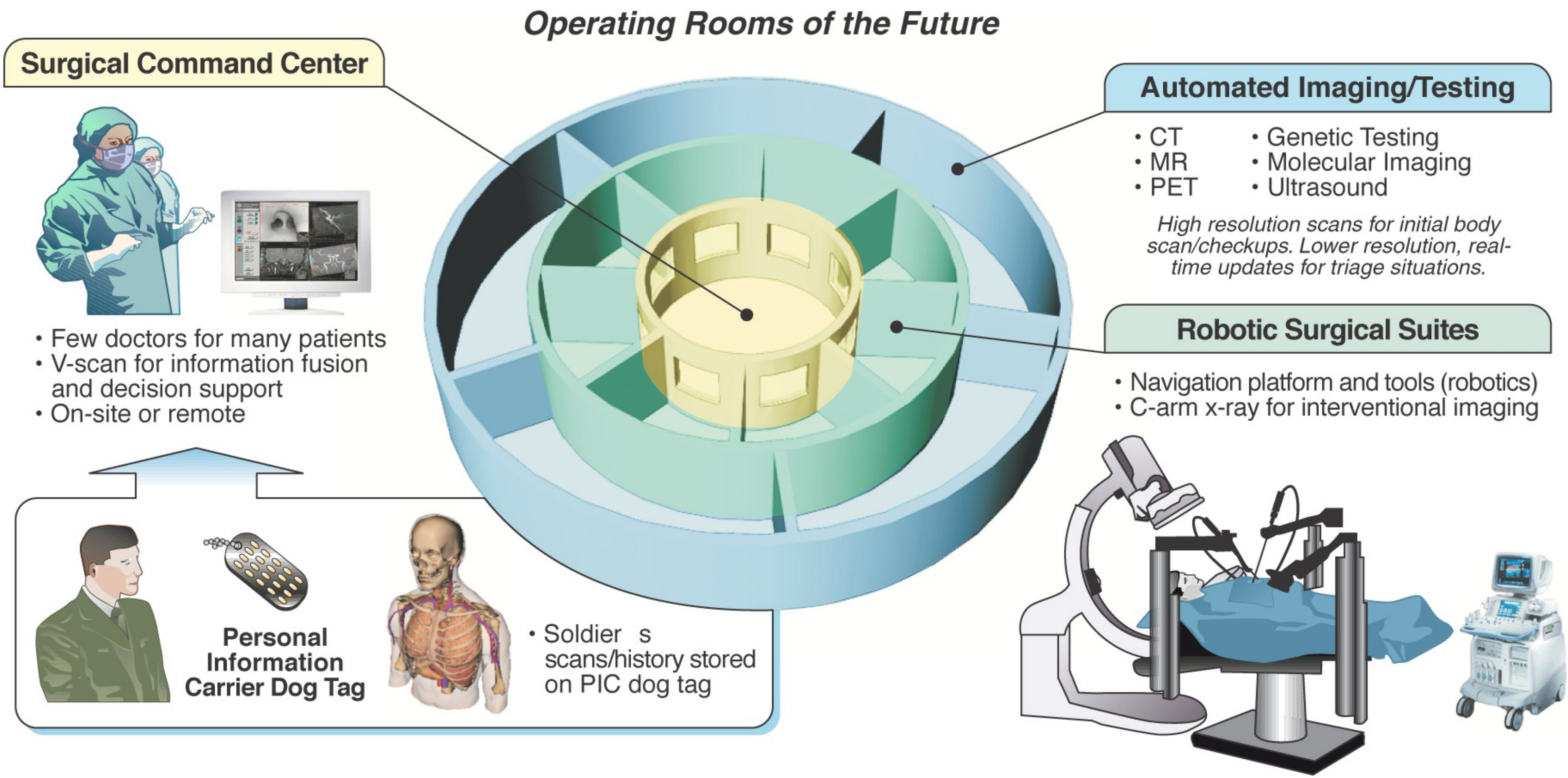
Anterior view of pericardium and mediastinum

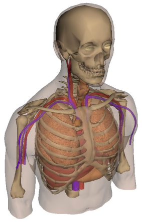
Left lateral view of mediastinum

Provided by Peter Ratiu, Harvard Medical School



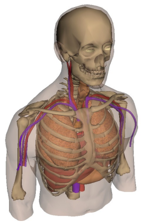
# OR of the Future





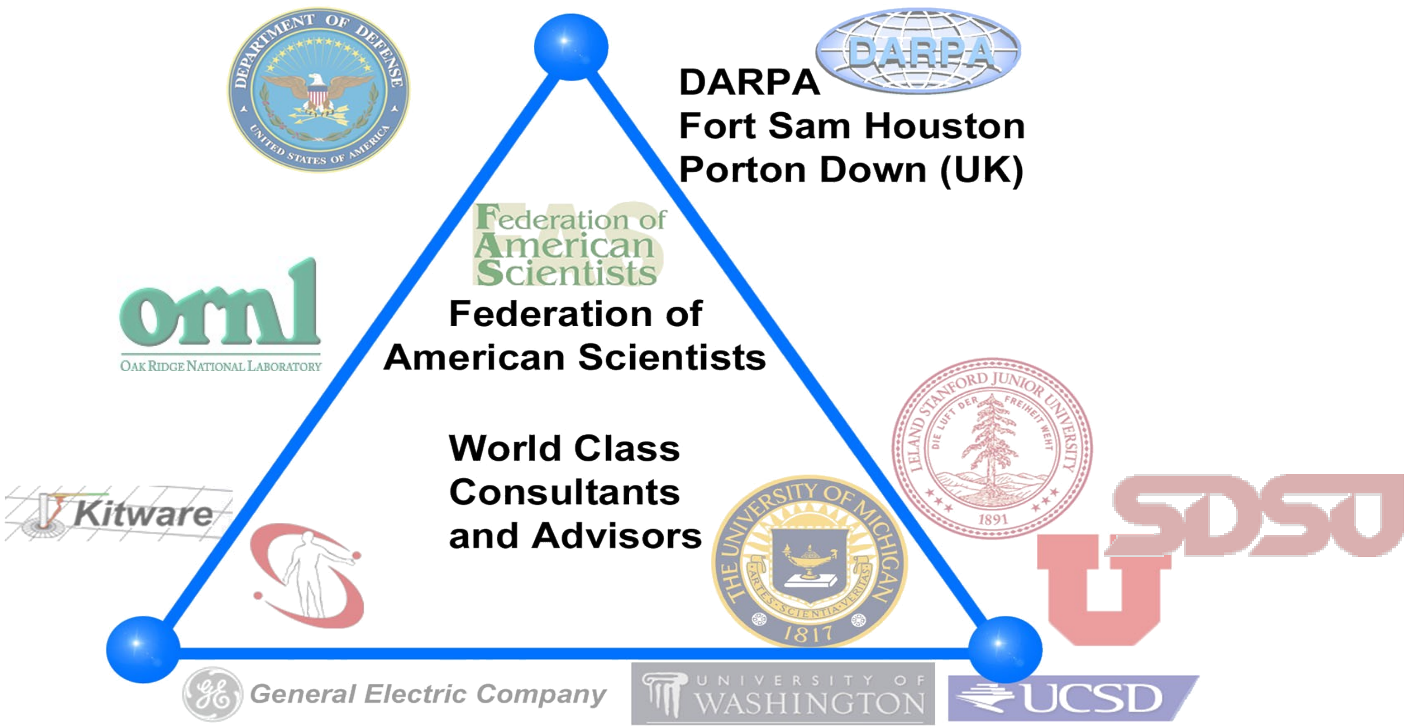
# External Interest

- Government
  - NASA, advanced medical care for astronauts
  - DARPA, Virtual Soldier, cell modeling for biological warfare
  - NIH, organ models
  - NSF, advanced computation methods
  - FBI, facial reconstruction, forensic analysis
- University
  - Univ of Utah, electro-mechanical cardiac modeling
  - Stanford, patient specific fluid flow
  - Harvard, clinical uses of segmentation/registration
  - Univ of Colorado, visible human data acquisition
  - Berkeley, cell modeling
  - Washington University, brain modeling



# DARPA Virtual Soldier Team

## Government

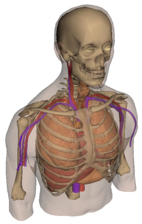



## Corporate

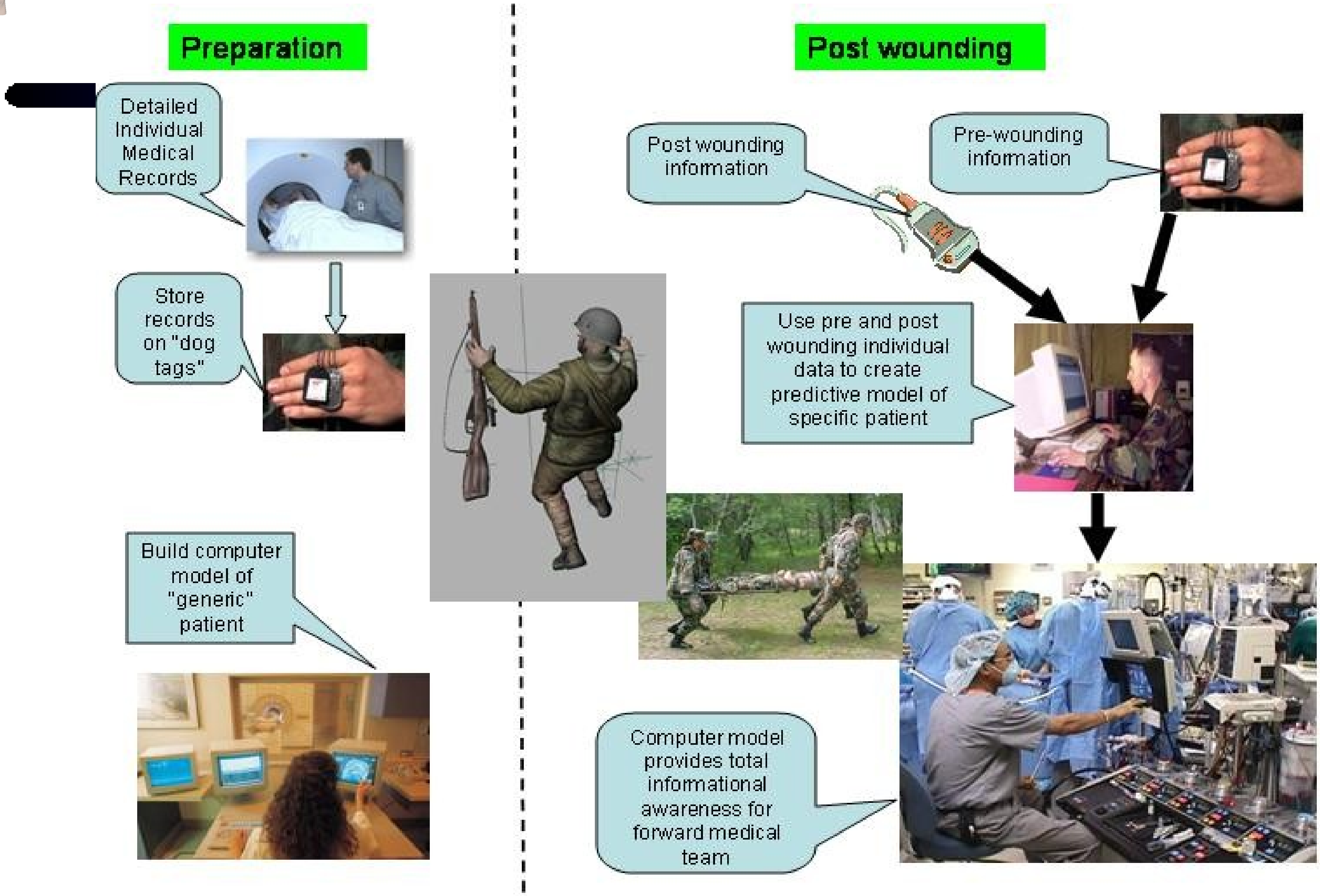
SimQuest International, LLC
General Electric Corporation
Kitware, Inc.

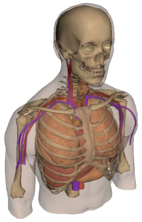
## Academic

University of Michigan
Stanford University
University of Washington
University of Utah
UCSD



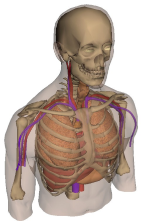
# The General's (DARPA's) View of the Virtual Soldier (Courtesy of Henry Kelly, FAS)



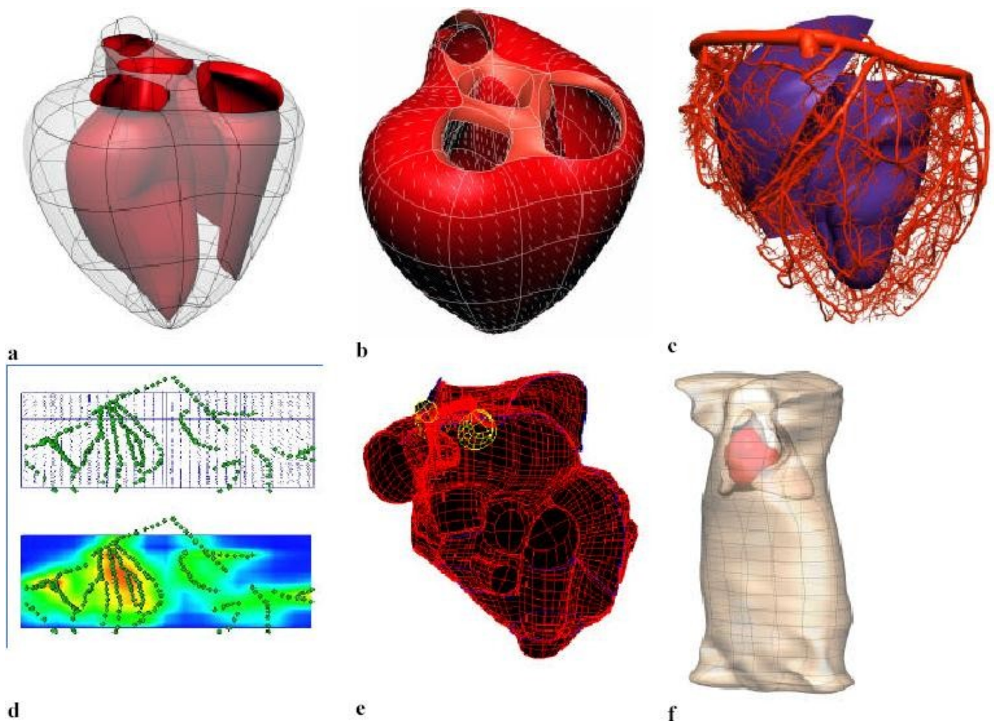


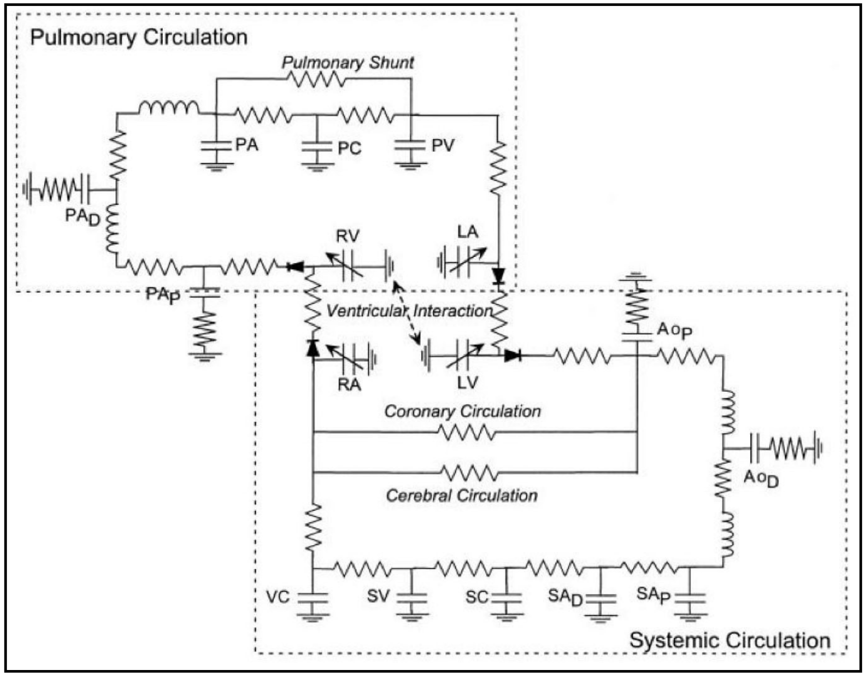
# *Virtual Soldier Buzzwords*

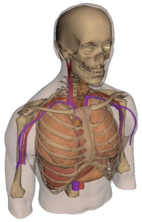
- “Holomer”—Virtual Representation of Individual Service Personnel.  Includes images, medical history, medical record informatic framework.  Sometimes called a “Body-Double”.
- “PIC”—Personnel Information Carrier.  Essentially a structured digital medical record stored on a flash memory chip.  A.k.a. “Electronic Dog Tag”.  Digital Record of the Holomer.



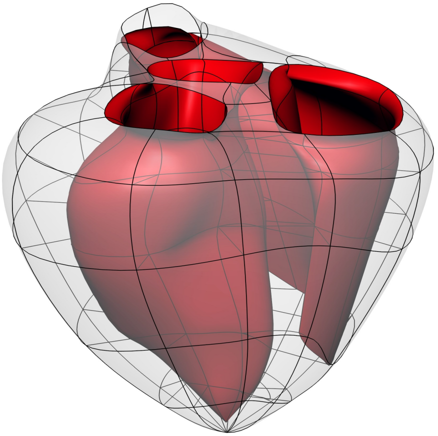
# *Anatomy, Physiology and Trauma Models provided by: Utah, UCSD, Auckland, UWash, Michigan, GE, and Mission Research*





# *Virtual Soldier Project: Cardiothoracic models*

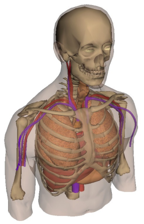


DESCRIPTION / OBJECTIVES / METHODS

- Multiscale integrative models of the heart
- Large-scale integration now feasible
- Use digital medicine to enhance battlefield care

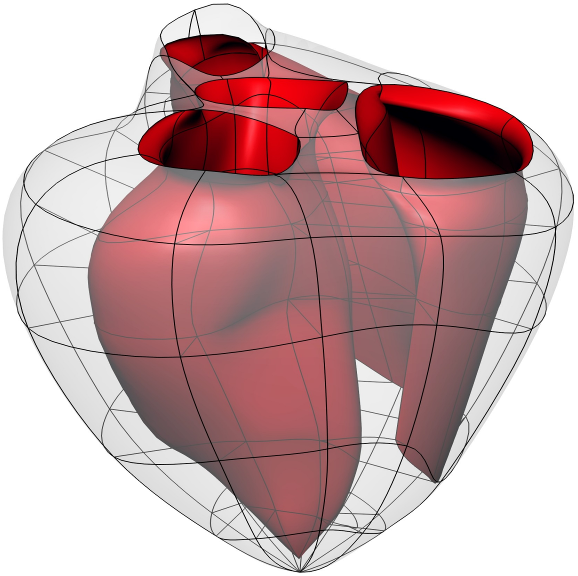
## Project Integration

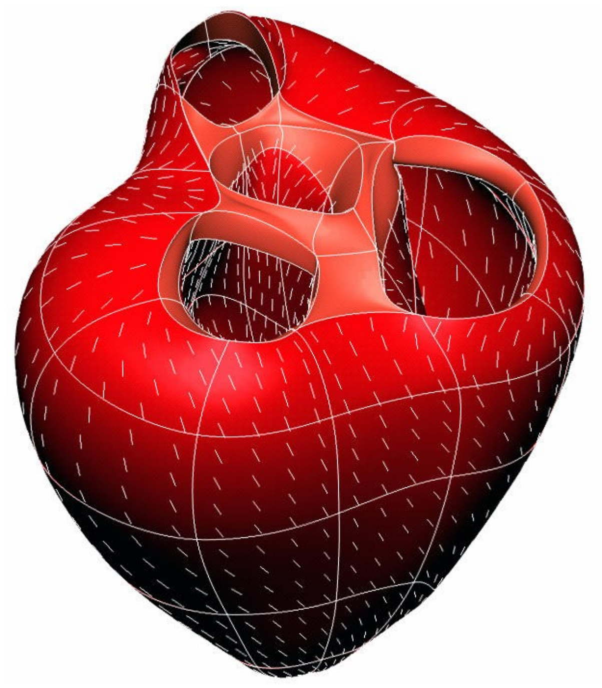
- **Univ. of Utah – deliver anatomic, electromechanical models;**
- **Univ. of Washington – anatomical models for markup with FMA ontology;**
- **Univ. of Washington – collaborate and integrate system models of circulatory dynamics and cell physiology;**
- **Univ. of Auckland – develop pig anatomy models;**
- **Mission Research Corp – identify and model injury regions;**



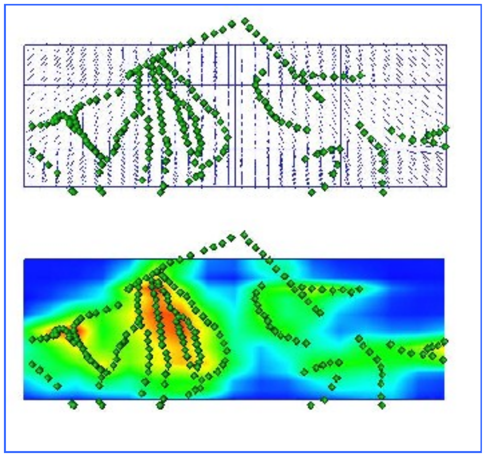
# Ventricular anatomy

## Auckland Pig Heart



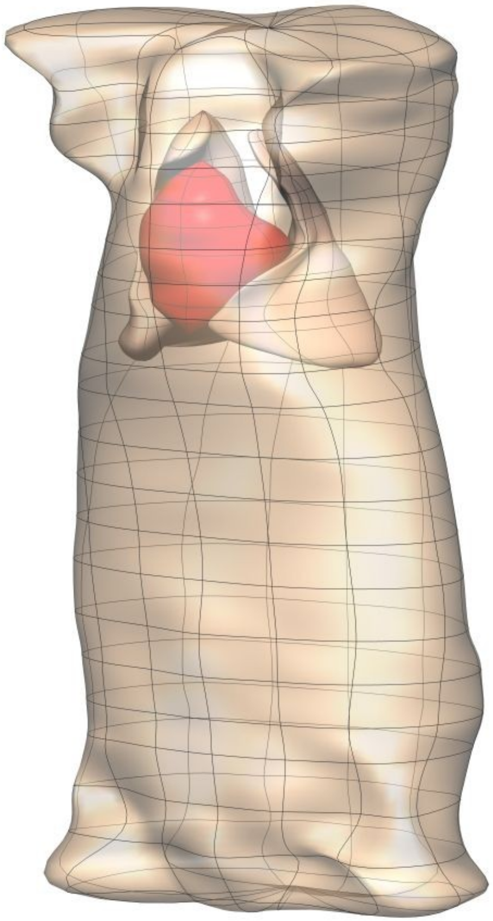


## LV Endocardial Model

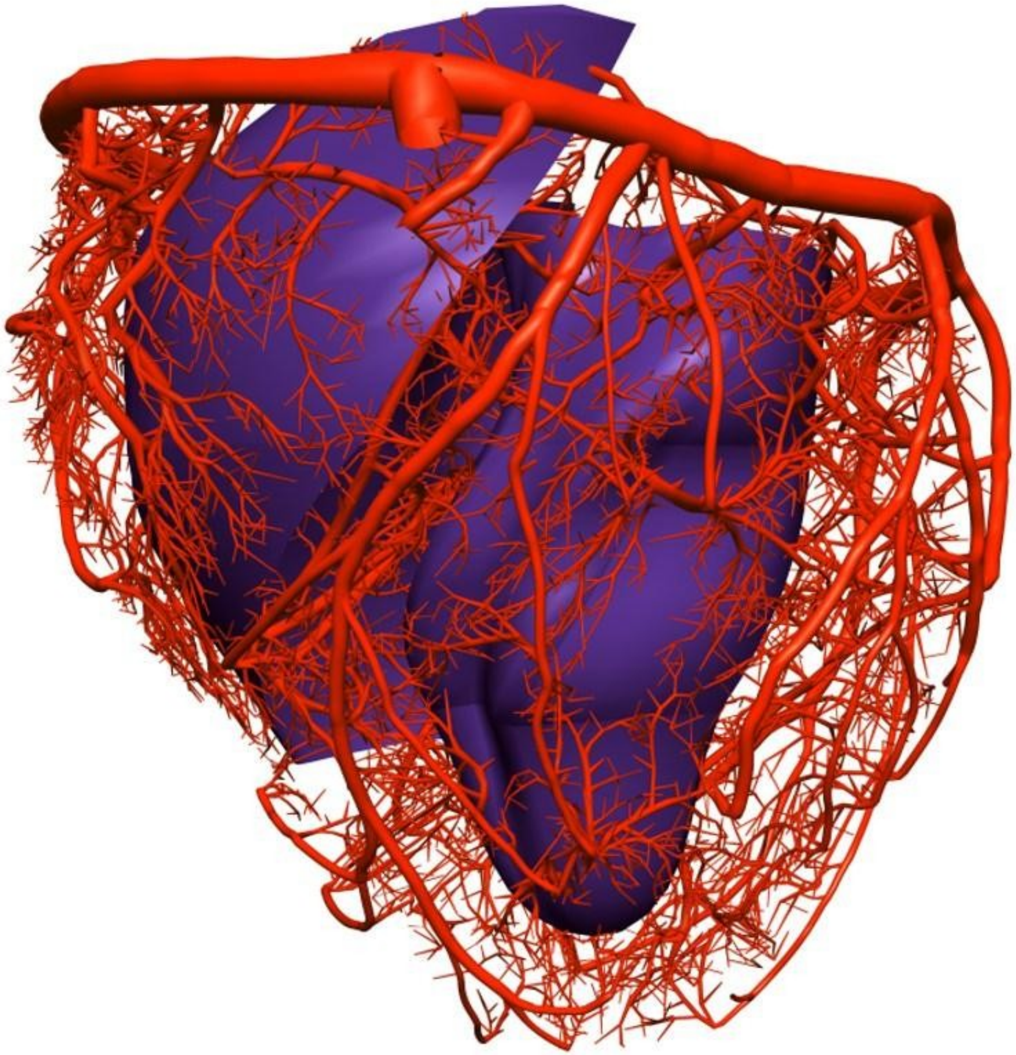


**Right and left ventricular anatomy**
**Fiber angle**
**Sheet angle**
**Purkinje fiber network**

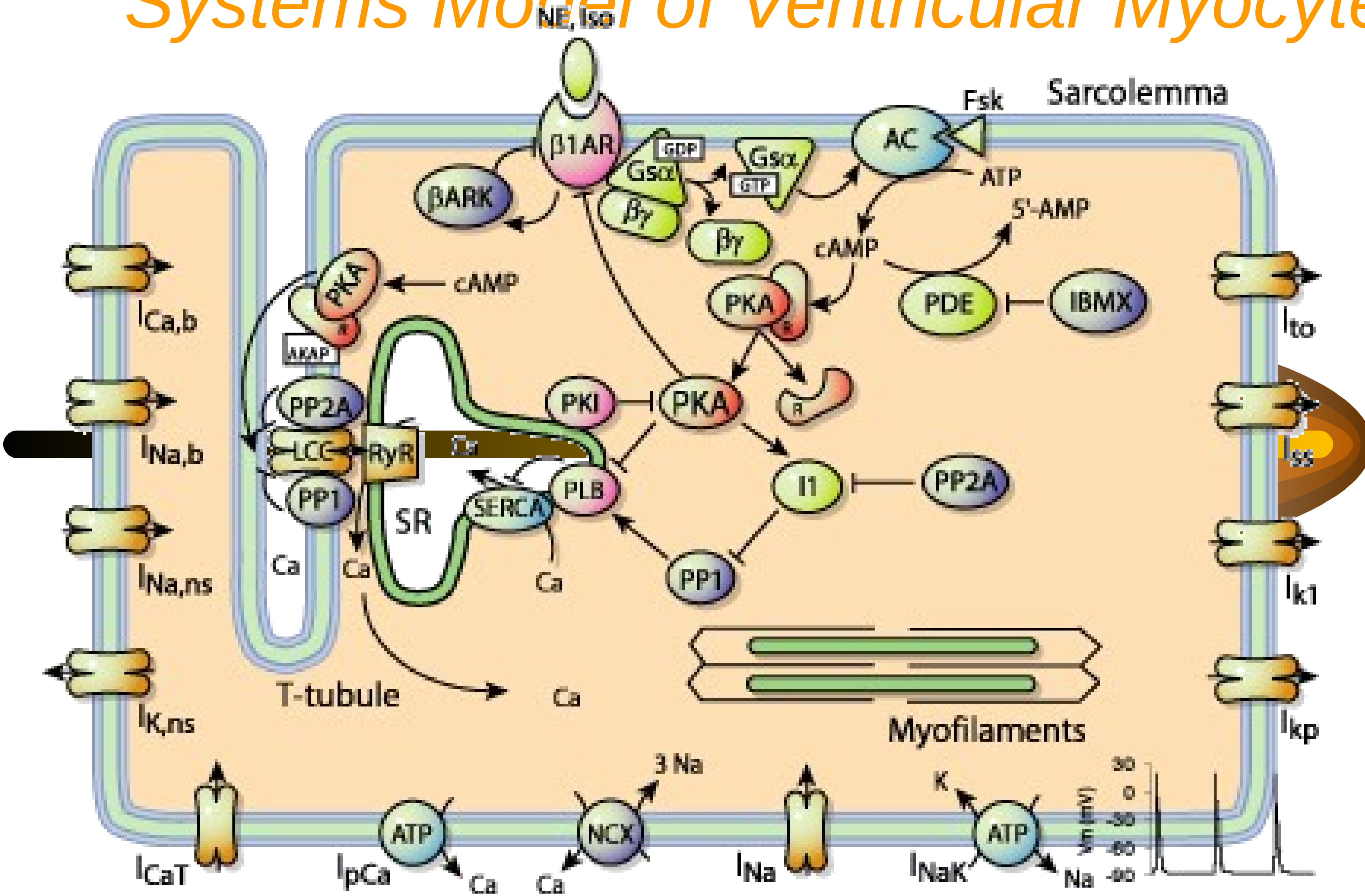
# Torso anatomy



# Coronary artery network

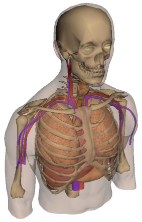


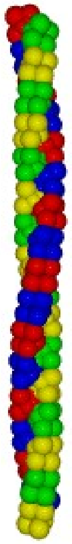
# Systems Model of Ventricular Myocyte



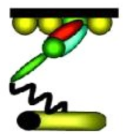

Saucerman JJ, Brunton LL, Michailova AP, McCulloch AD. Systems analysis of β-adrenergic control of cardiac myocyte contractility. *J Biol Chem* 2003 (in press)

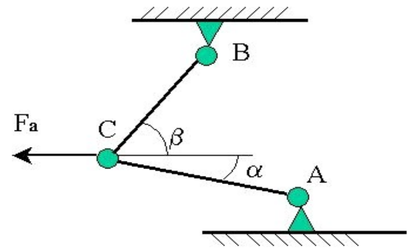
# *Structural Integration*
# *Myocardial Mechanics*



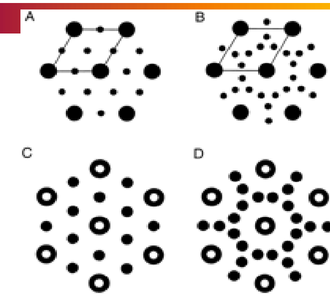


**filament**

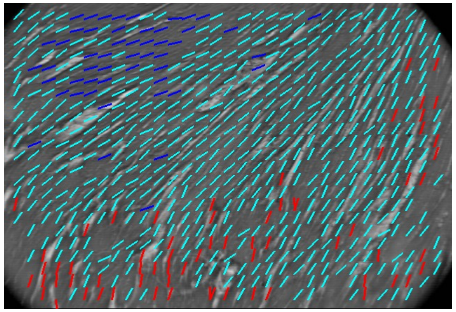




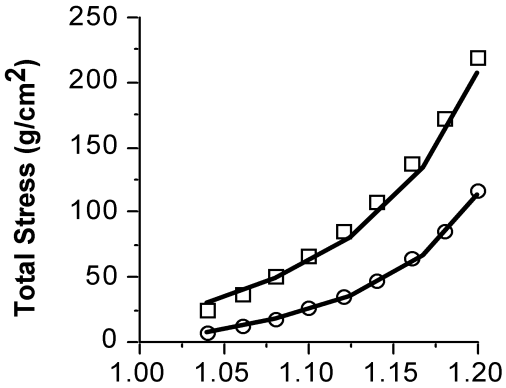

**crossbridge**




**lattice**

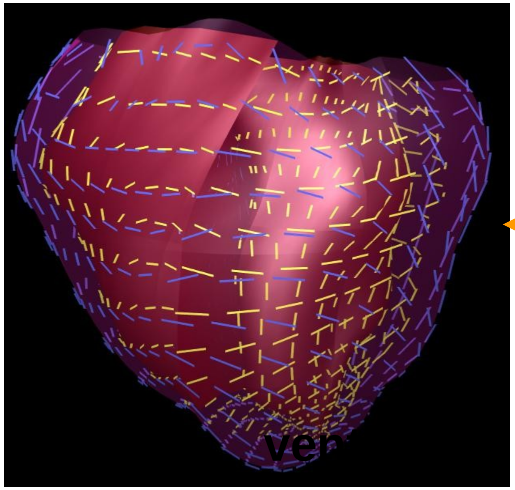


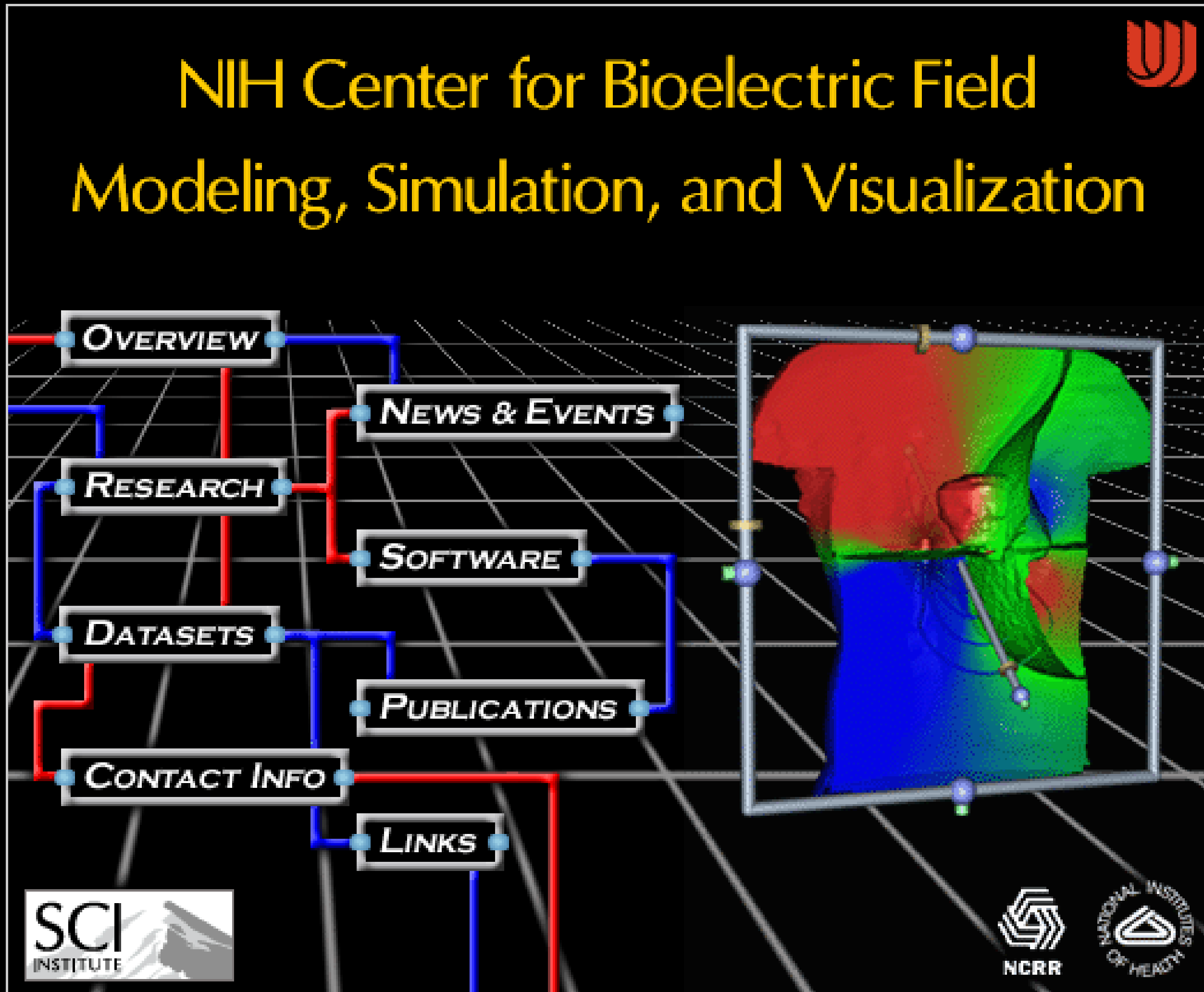
**multicellular**




**myocardial tissue**

Lin DHF, Yin FCP (1998) *J Biomech Eng* 120: 504-517.



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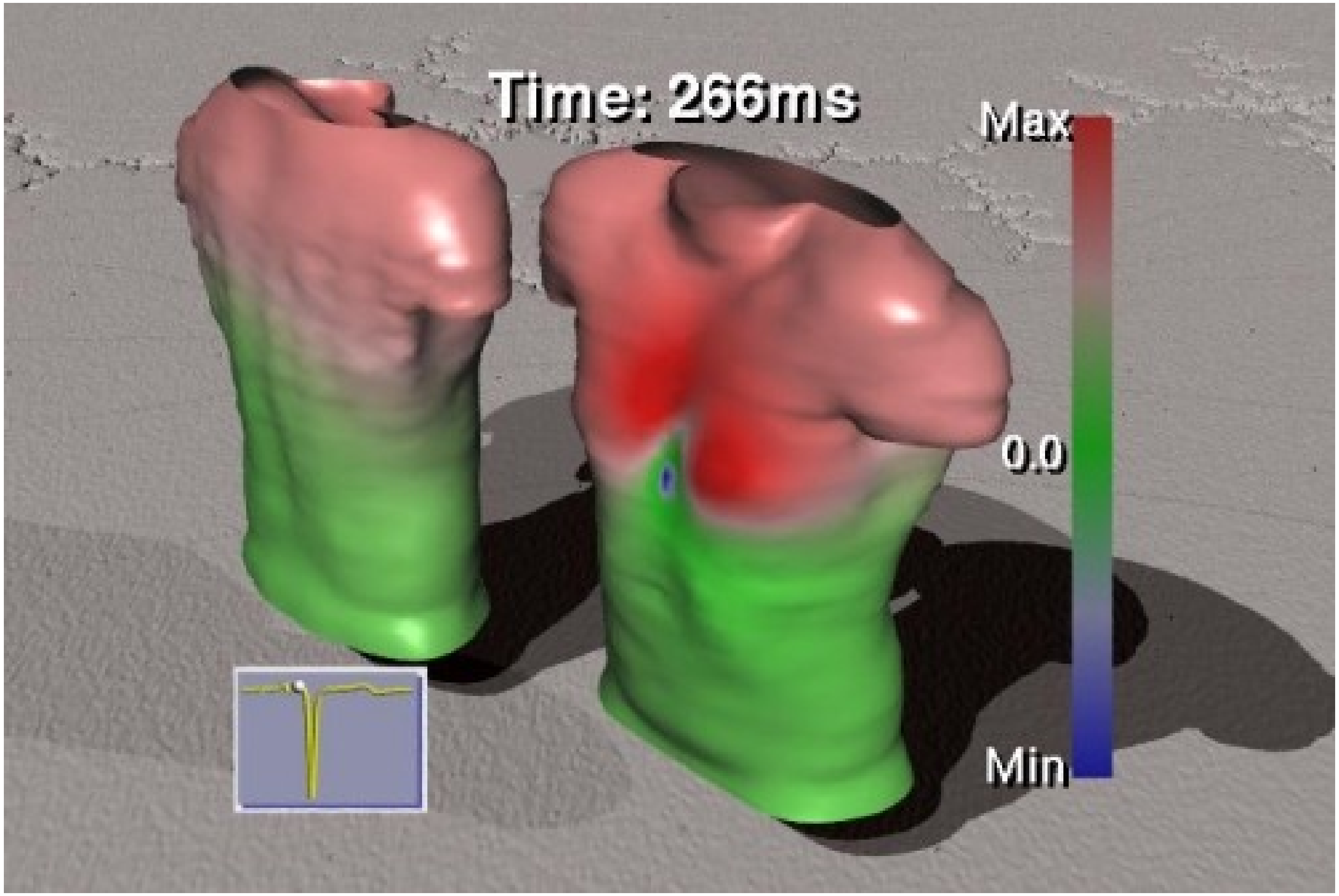
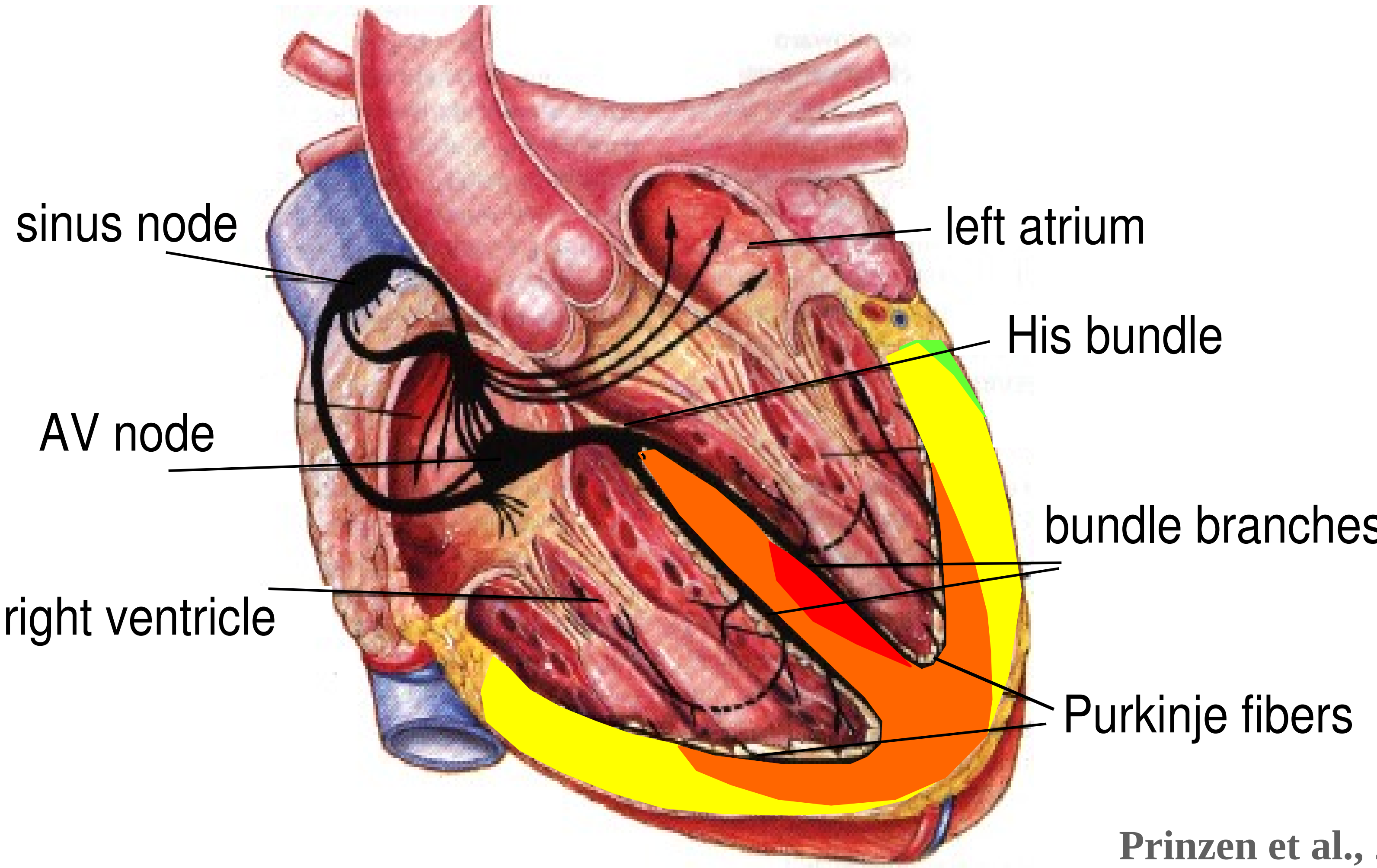
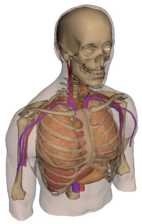
# Bio-electric field modeling



# Electrical activation of the normal heart

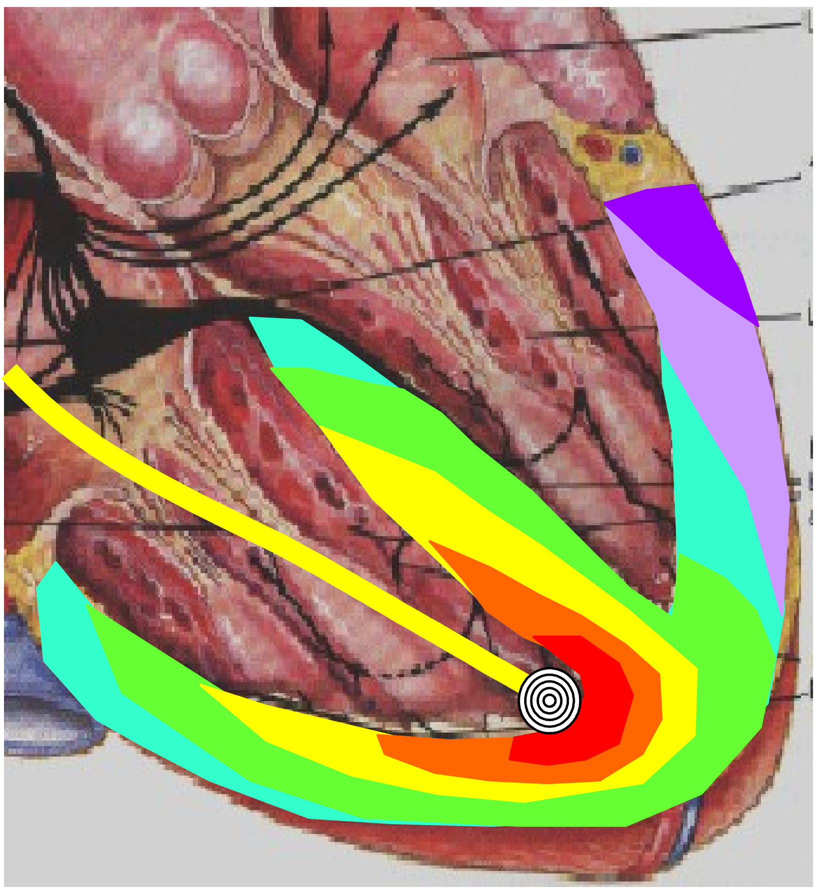



Prinzen et al., 2000

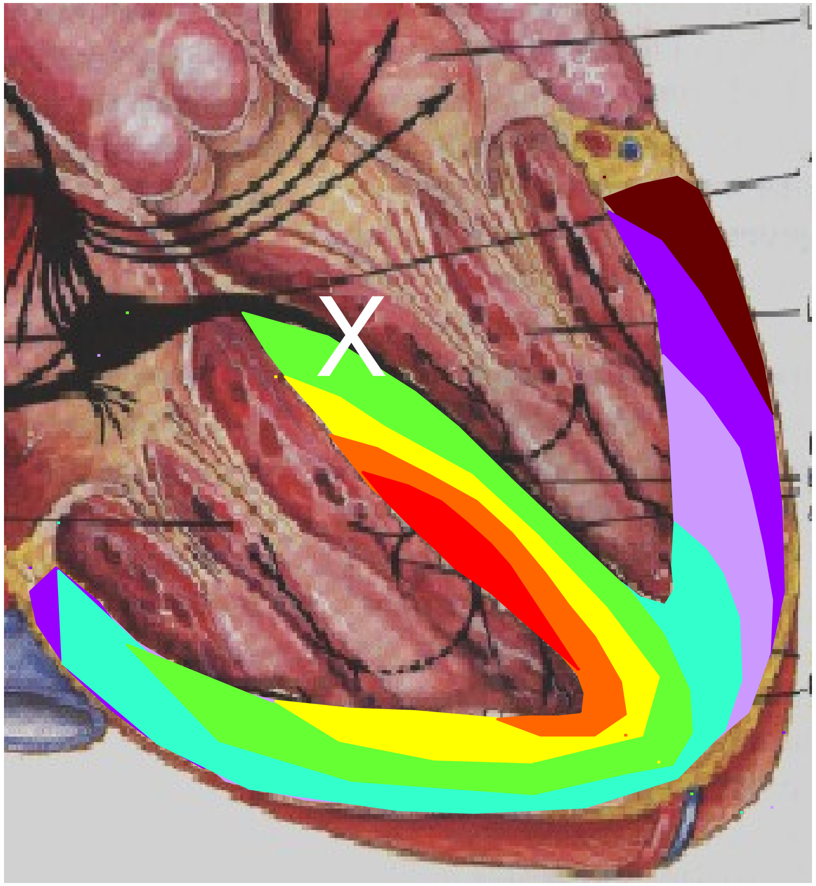


# Schematics of electrical activation

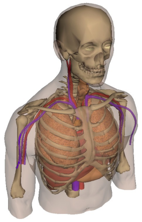
RV apex pacing



Left bundle branch block

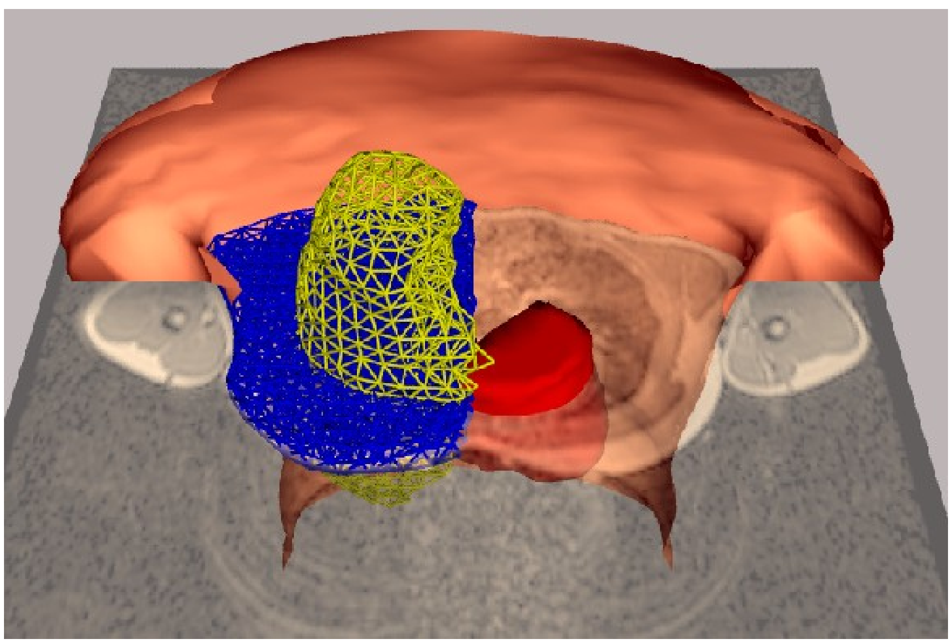


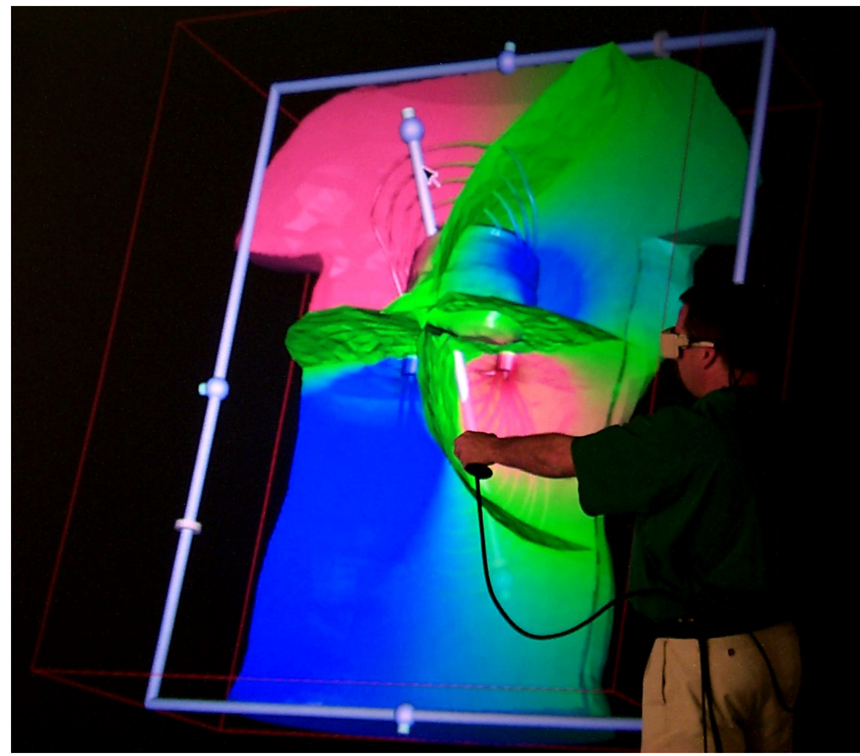

Prinzen et al., 2000

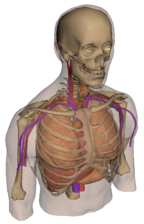


# Computation Workbenches

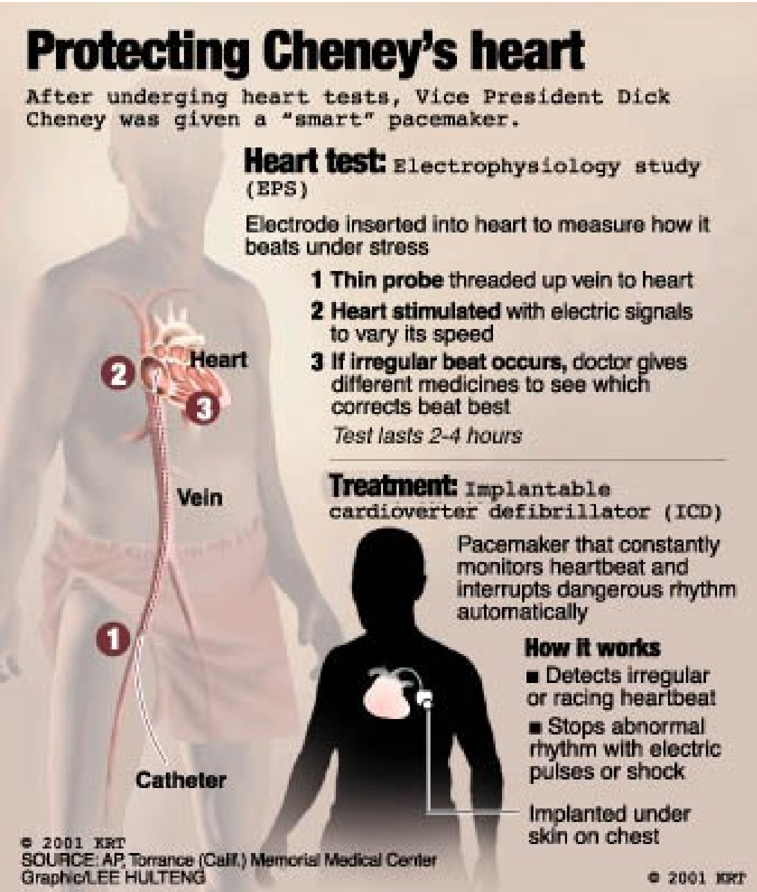
- Mission: Common Framework for Bioelectric Field Research
  - Exchanging tools and datasets
  - Presenting results
  - Comparing methods

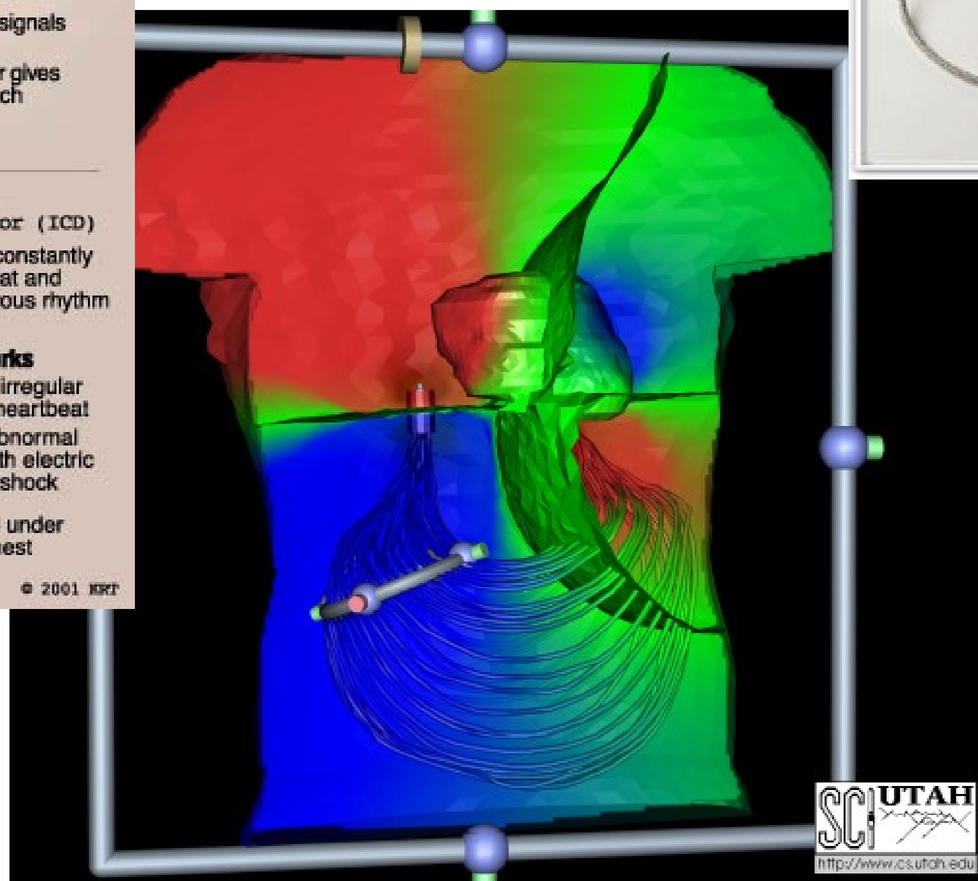




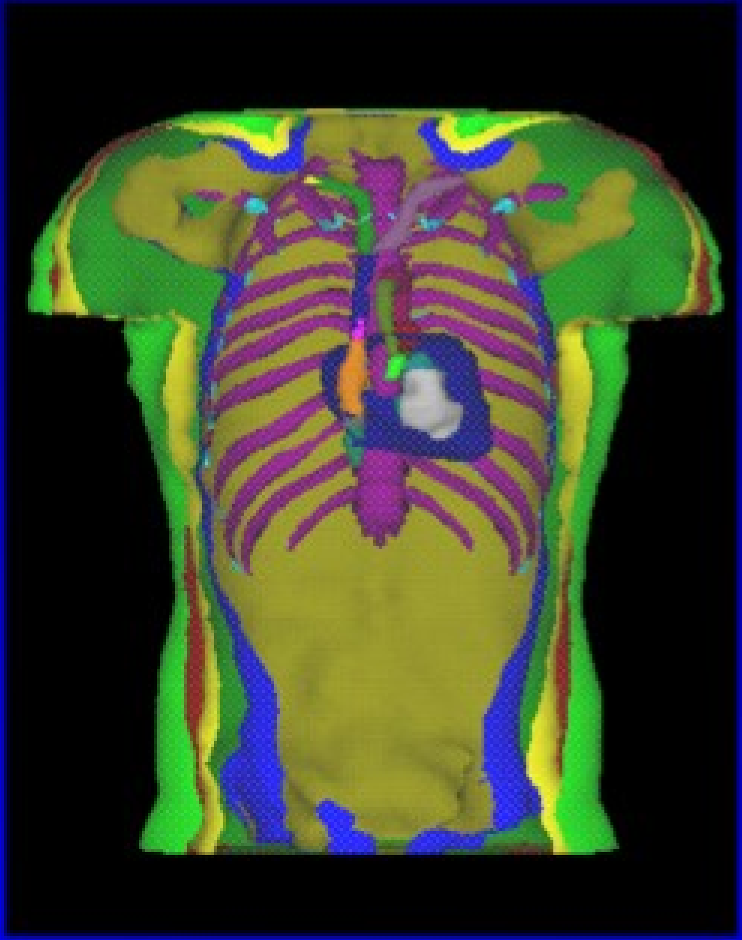


# Device Design: Defibrillation



# Geometry of Utah Torso Model

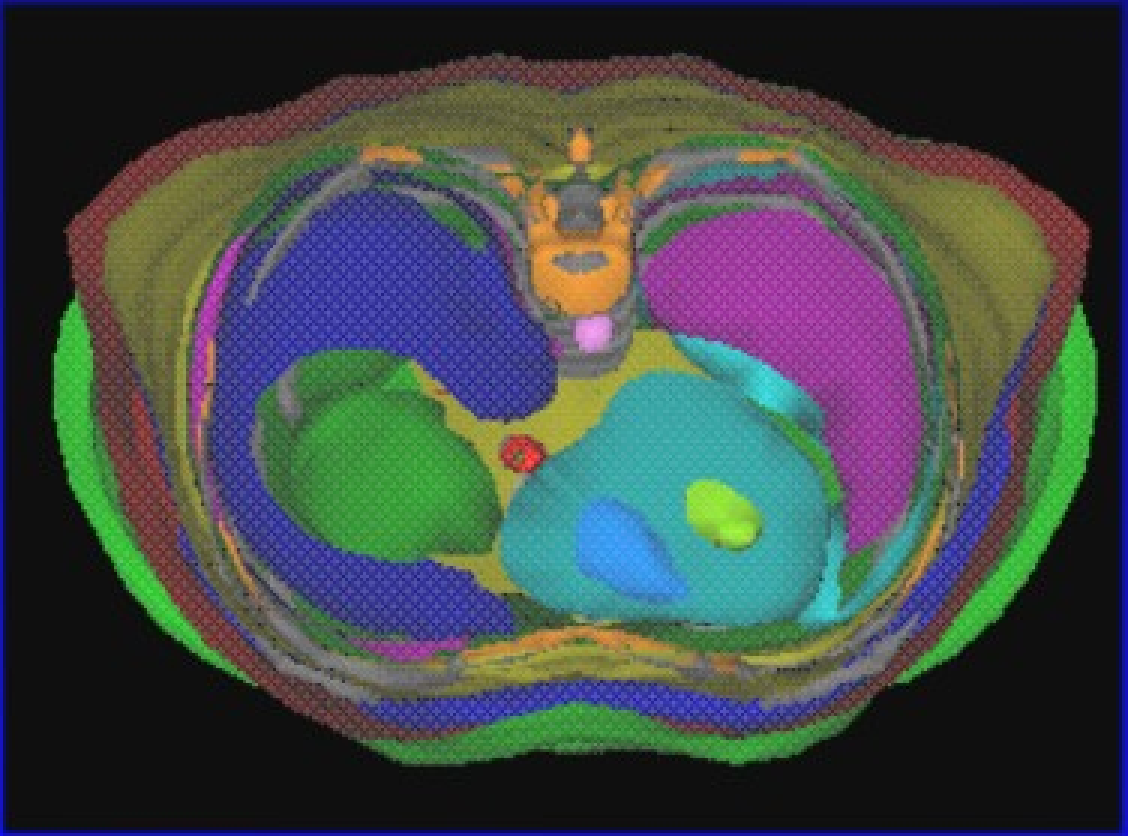


**Geometry Includes:**

- Subcutaneous Fat
- Skeletal Muscle
- Lungs
- Ribs
- Heart
- Blood Cavities
- Major Blood Vessels

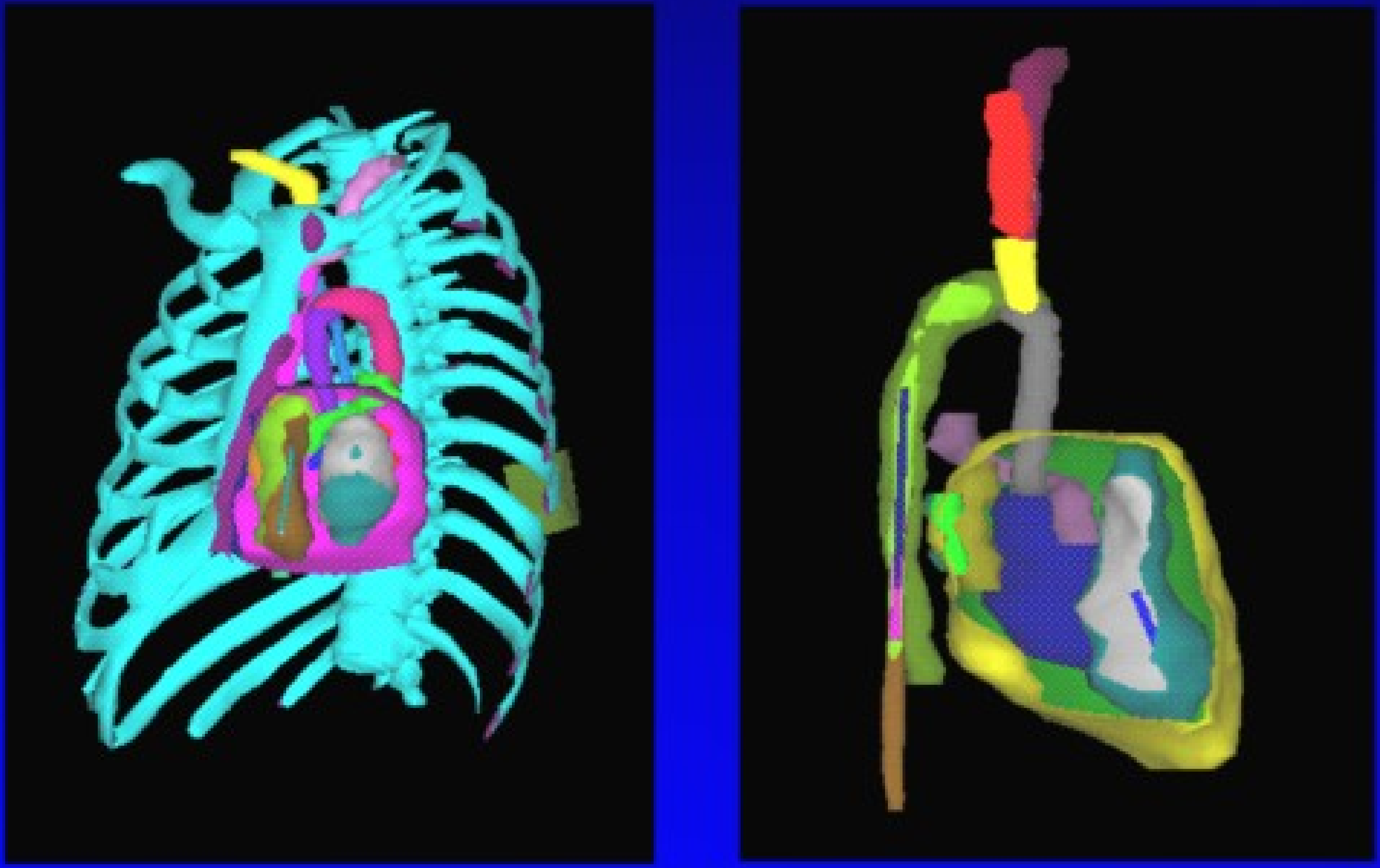
SCI UTAH

# Cross Sectional View of Thorax



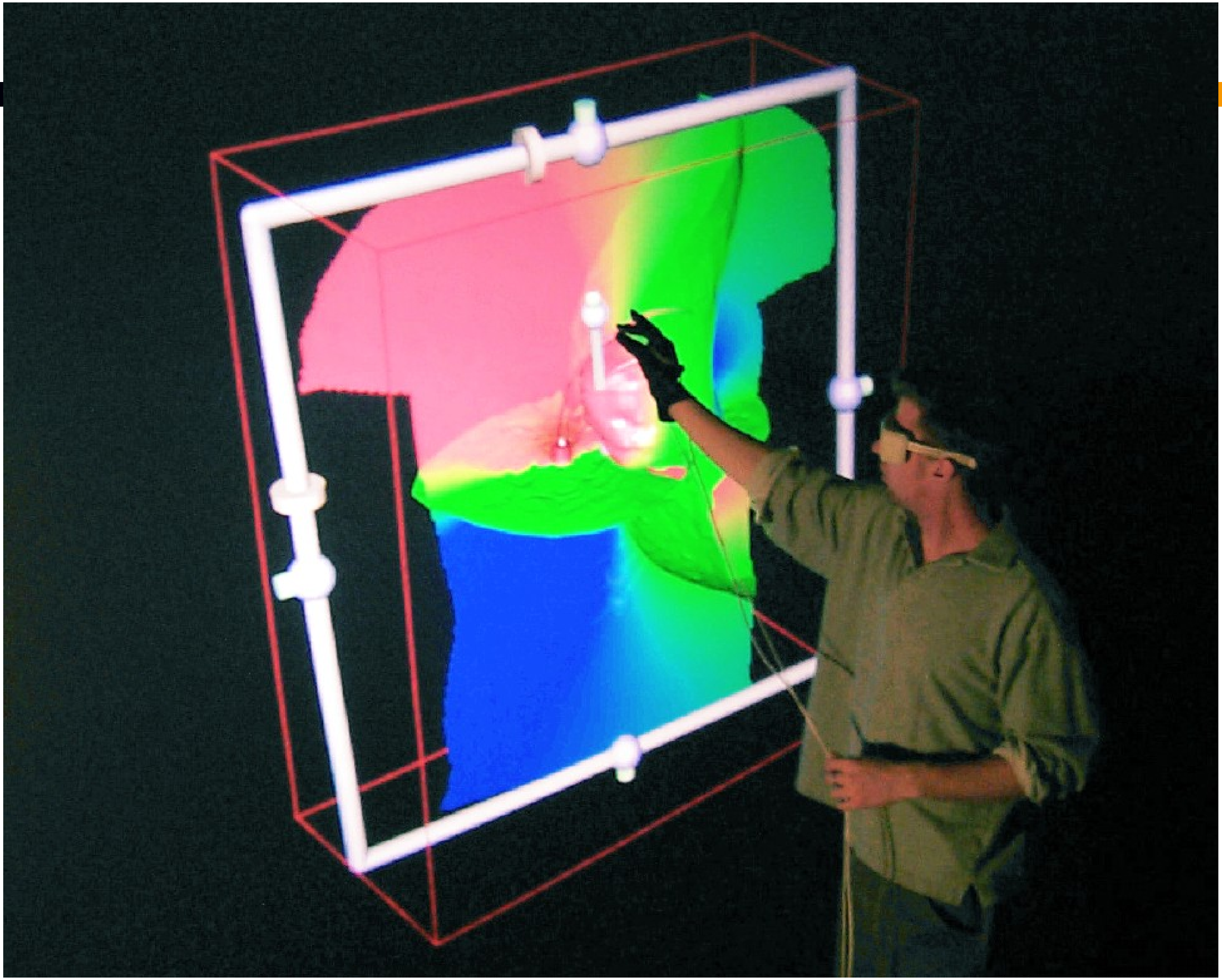
SCI UTAH

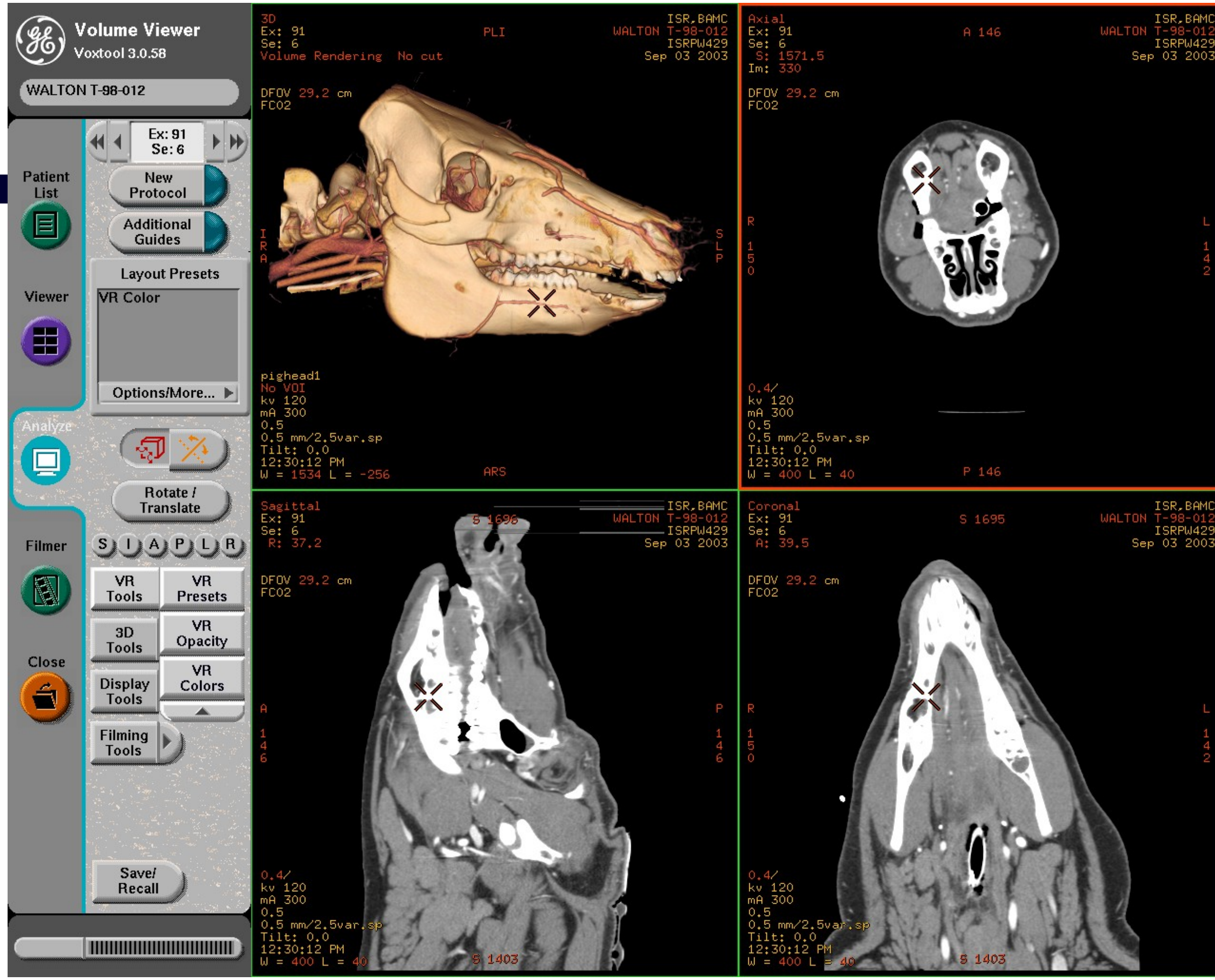
# Internal Electrode Locations



SCI UTAH

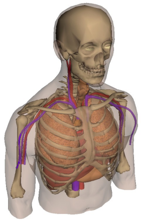
# Immersive ECG Environment

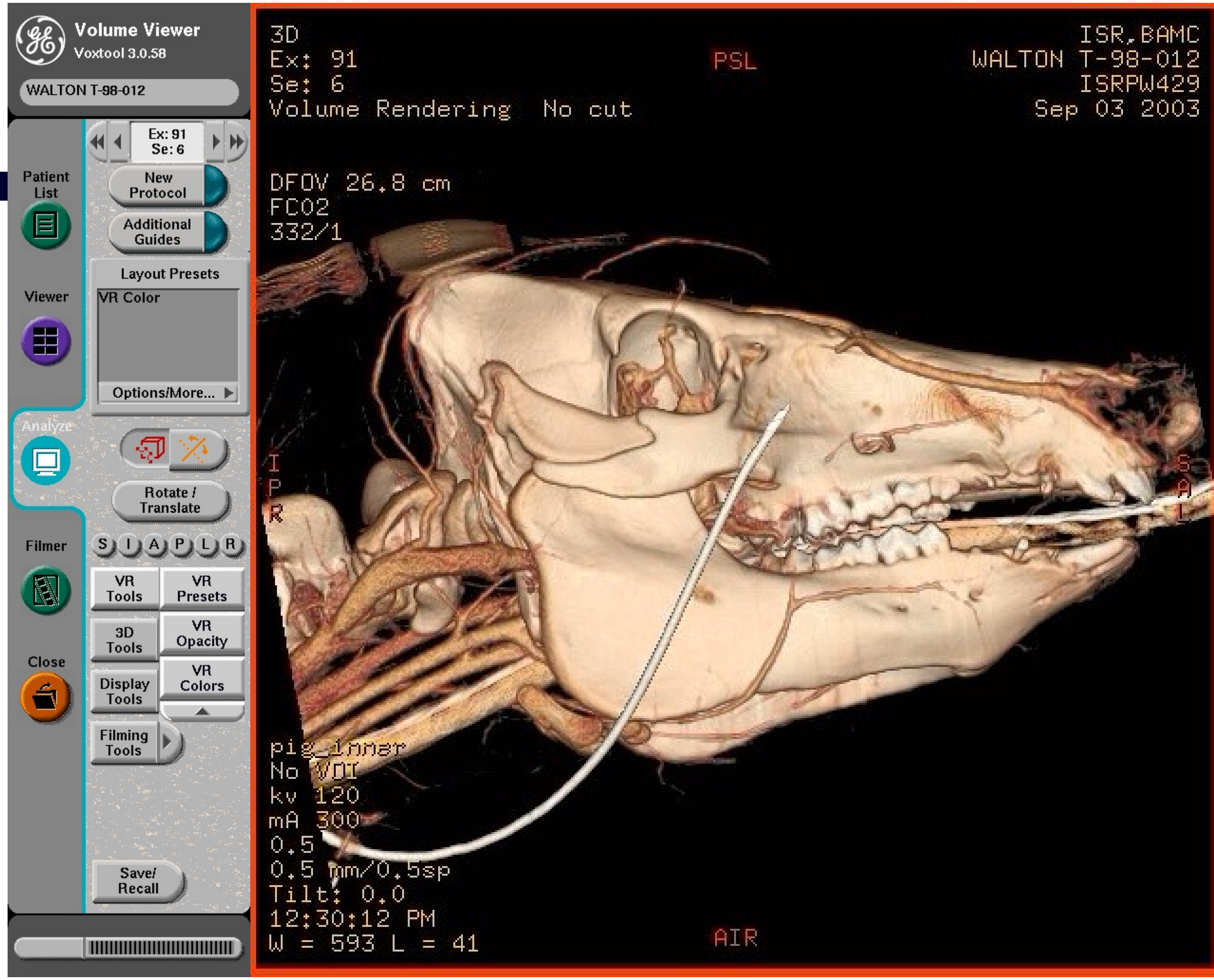




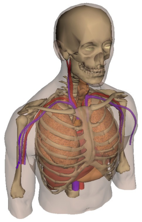

*Data courtesy LTC Ron Walton, DVM, MS*

*US Army Institute of Surgical Research, Ft Sam Houston, TX*

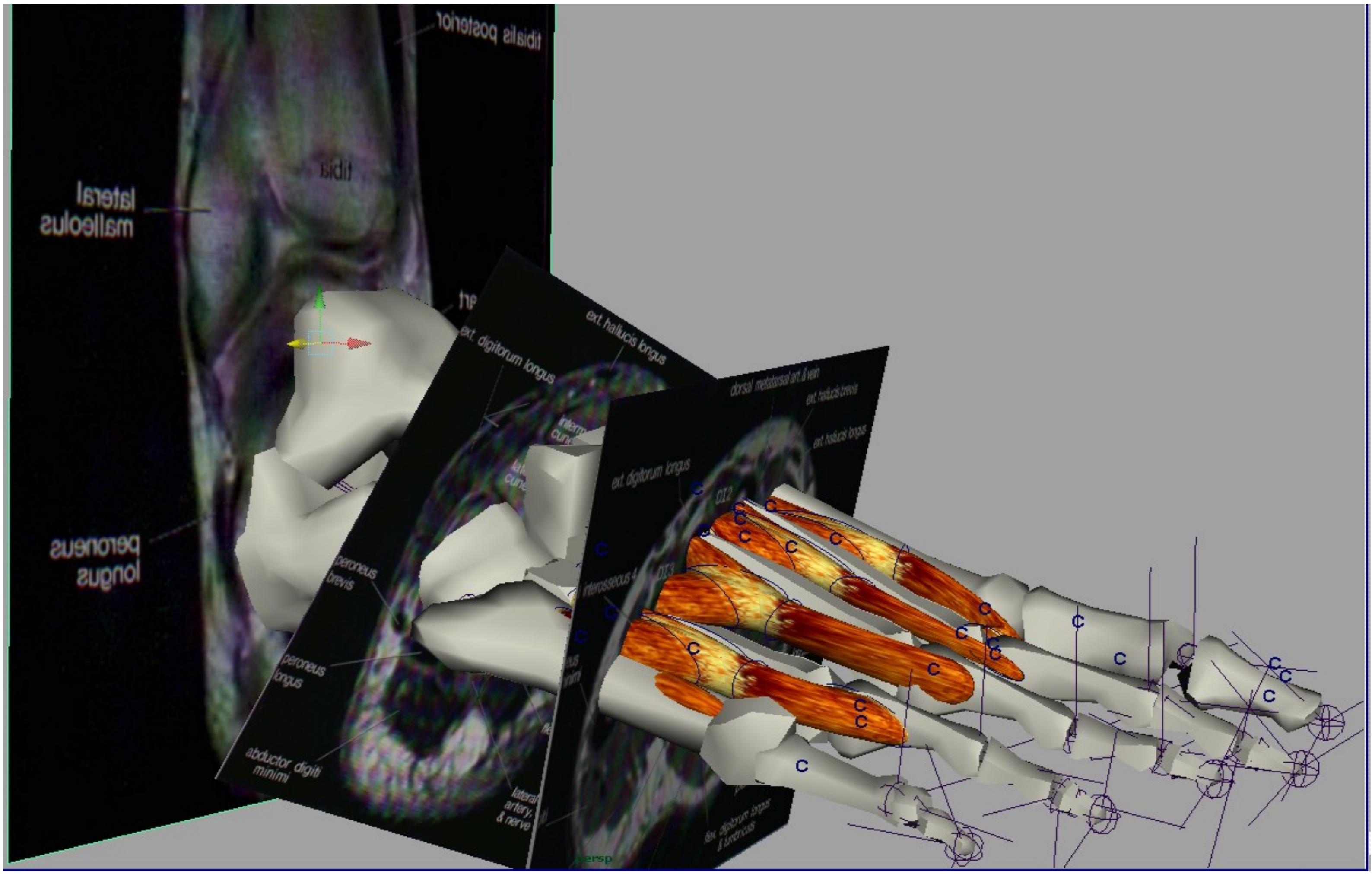


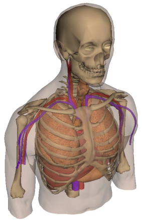



*Data courtesy LTC Ron Walton, DVM, MS*
*US Army Institute of Surgical Research, Ft Sam Houston, TX*



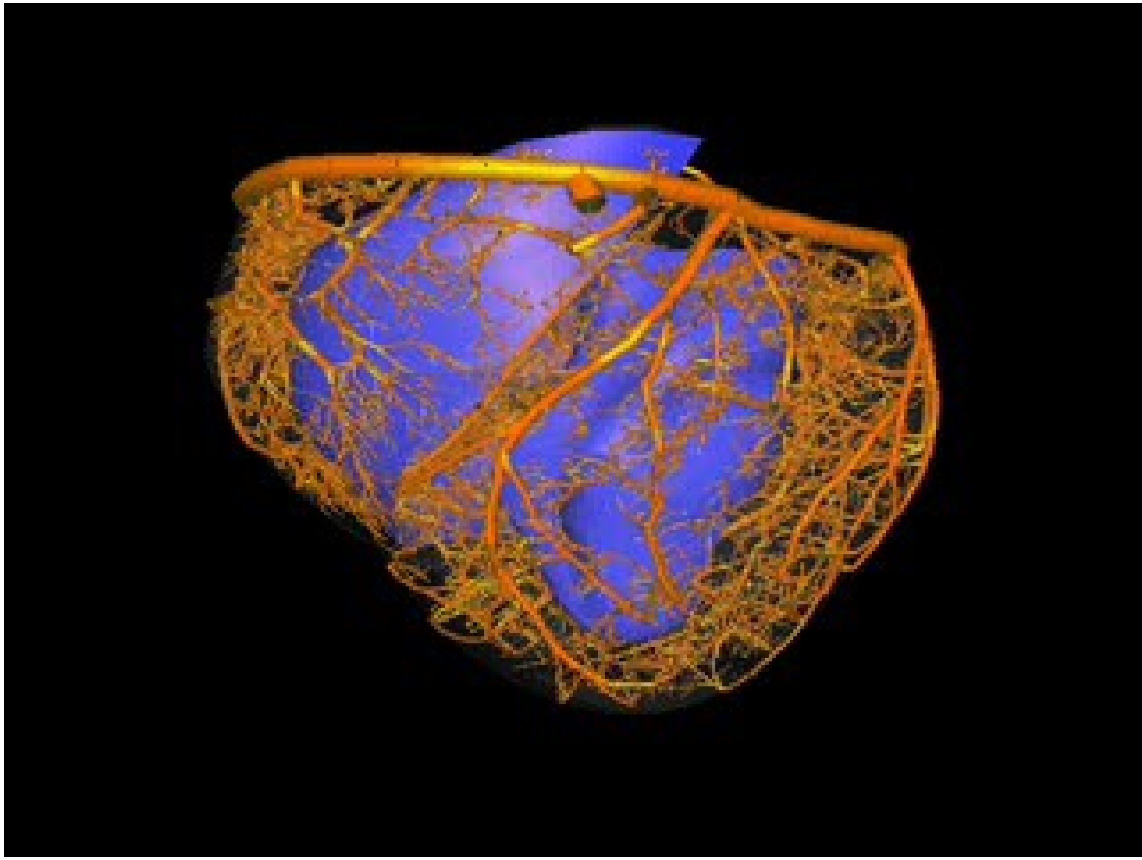
# Ontology-Based 3D Modeling for Human Anatomy





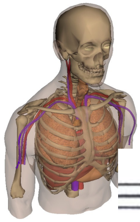
# Integration by Computation The Cardiome

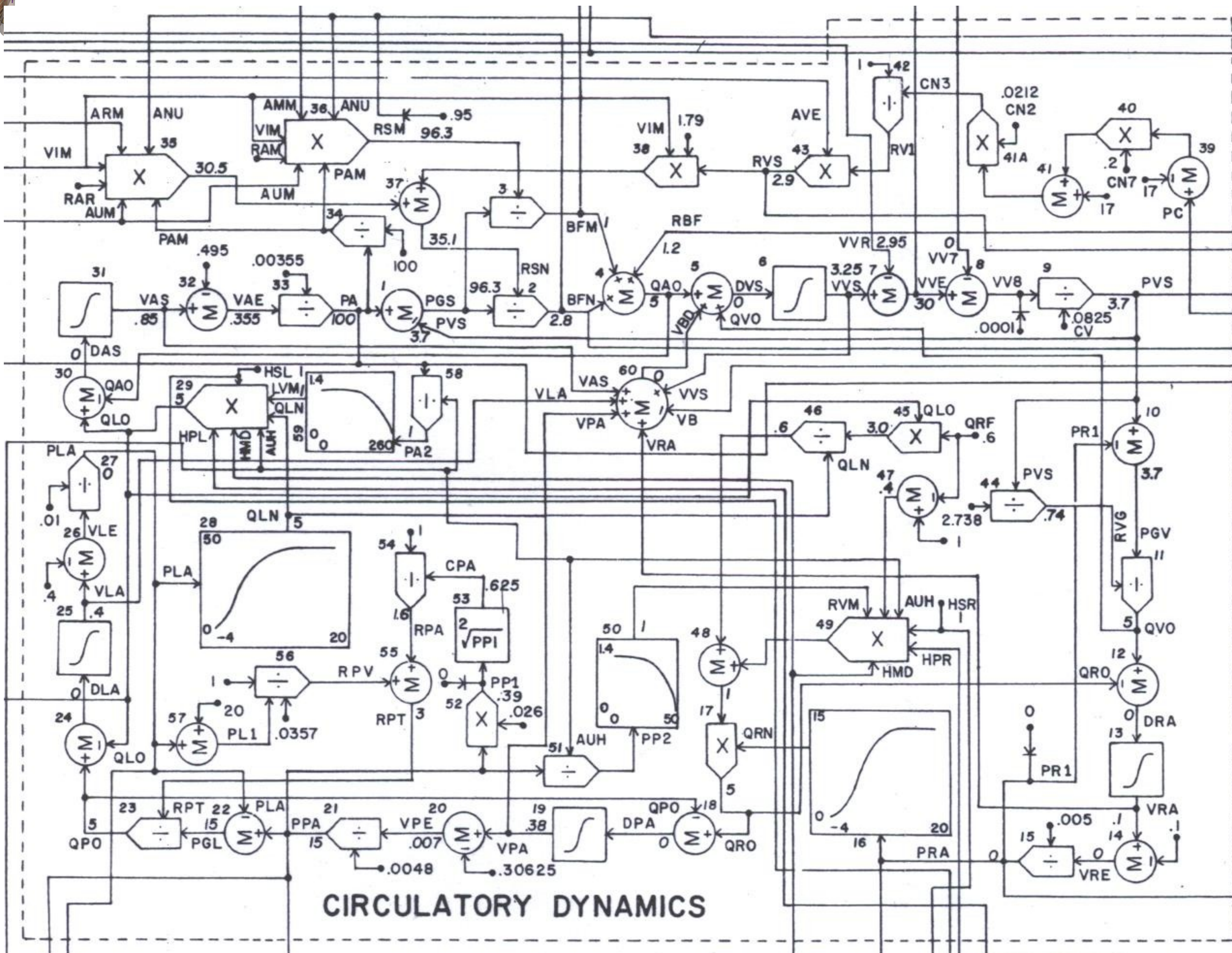
- Transport:
  - UWash Flows, uptake ($O_2$, fats), nucleotide energetics
- Cardiac Mechanics:
  - Auckland Univ: P.Hunter
  - UCSD: McCulloch
  - Maastricht: Arts, Prinzen, Reneman
  - JHU: W.Hunter
- Action Potentials:
  - Oxford U: D. Noble
  - Johns Hopkins: Winslow
  - Case-Western: Rudy
- Cardiac excitatory spread:
  - CWRU: Rudy et al.
  - Johns Hopkins: Winslow
  - Syracuse: Jalife
  - UCSD: McCulloch

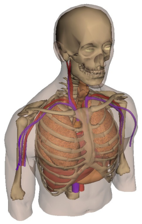


N.Smith, P. Hunter,et al. 1998

(Guyton et al., 1972)

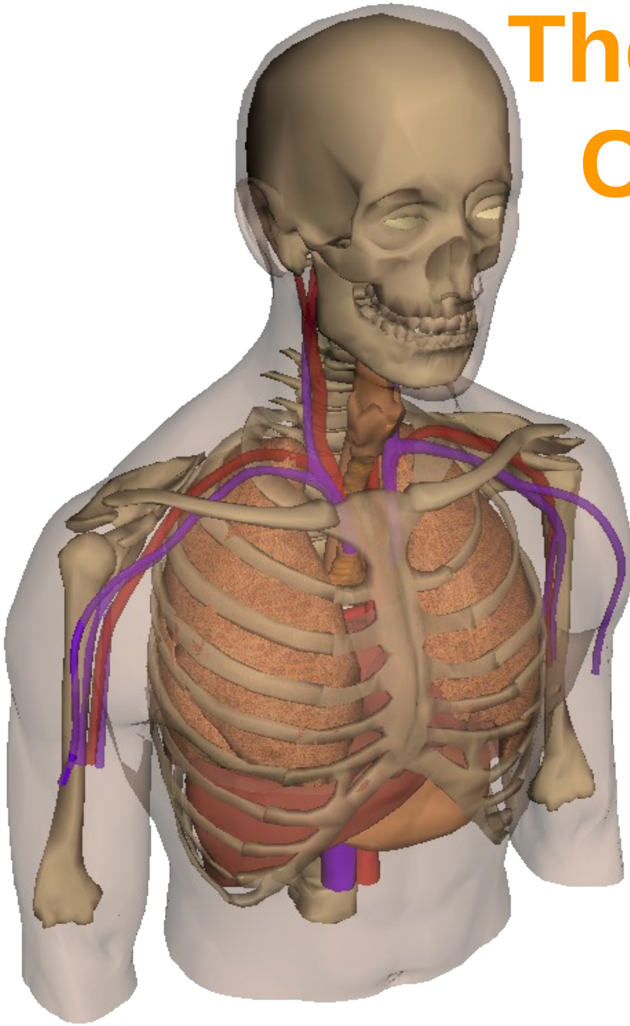






# Next Steps

- Establish coordinated funding from multiple institutes
  - Multiple NIH Institutes
  - NSF
  - DARPA
  - DOE
  - NASA
- Large scale systems integration effort is required
  - This may require non-standard funding



# The Digital Human: Using Computers to Improve Health

*Bill Lorensen*

*GE Global Research*

*Niskayuna, NY*

*lorensen@crd.ge.com*