BioGears: An OpenSource Human Physiology Engine

Agenda (1:30pm – 5:00 pm)

1. Engine Overview **[~50min]**
- *Bio Break* **[10min]**
2. Using the Graphical User Interface (GUI) **[~50min]**
- *Bio Break* **[10min]**
3. Interacting with the Application Program Interface (API) **[~50min]**
4. Questions and Help **[until 5pm]**

Recommended Preparation

- If you would like to follow along using the GUI (item 2), please download and unzip the Toolkit from: https://biogearsengine.com/download

BioGears Overview

Presentation for MMVR

Presenters: Jeff Webb, Rachel Clipp, PhD, Aaron Bray
Applied Research Associates, Inc. (ARA)
7 April 2016

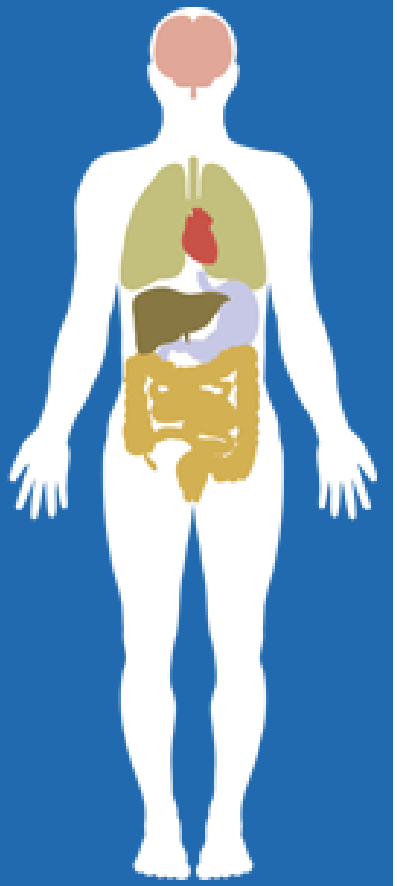
BioGears Overview Agenda

- Program Overview
- Modeling Approach
- Verification and Validation
- Systems Review
- Architecture and Tools
- Coming Soon

PROGRAM OVERVIEW

Project Information

- **Organization:** Applied Research Associates, Inc. (ARA)
- **Telemedicine & Advanced Technology Research Center (TATRC)**
  Award #: W81XWH-13-2-0068
- **Principal Investigator:** Mr. Jeff Webb
- **Amount:** $6,959,593
- **Period of Performance:** Sept 2013 – Sept 2018
- **License:** Apache 2.0 permissive free software
- **Disclaimer:** *This work is supported by the US Army Medical Research and Materiel Command. The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision unless so designated by other documentation.*



High Level Objectives

- Create a **publicly available** physiology research platform that enables accurate and consistent simulated **physiology** across training applications
- **Lower the barrier** to create medical training content
- **Engage the community** to develop and extend physiology models
- Meet the **training needs** of the military
- **Expand** the **body of knowledge** regarding the use of simulated physiology for medical education

biogears

Physiology Engine Overview

Patients

Personalized Configuration

Equipment

Anesthesia Machine

Inhaler

External Systems

System Interactions

Environment
Substances & Thermal

Internal Systems

Cardiovascular
Hemodynamics & ECG

Respiratory
Gas Exchange

Blood Chemistry
Quantities & Panels

Renal
Blood Filtering

Nervous
Sympathetic & Parasym.

Endocrine
Hormones

Gastrointestinal
Ingestion

Energy
Thermal & Metabolic

Drugs
PK/PD

Features

Organs & Tissues
Extravascular & Intravascular

Homeostatic Feedback
- Baroreceptors & Osmoreceptors
- Chemoreceptors
- Local Autoregulation

Physics Based Approach
- Fluid Mechanics – Gases & Fluids
- Thermodynamics – Heat Transfer

Substances
Transport, Diffusion, & Clearance
- Gases
- Hemoglobin
- Ions
- Hormones
- Nutrients
- Drugs

Interfaces

Inputs
- Parameter Setting
- Chronic Conditions
- Insults
- Interventions

Outputs
- Acute Events
- Clinical Assessments
- System Vitals
- Compartment Data

Scenarios
- Static and Repeatable and/or
- Real-Time Dynamic

ARA

Milestones

Link to Version History

FY13	September: project kick-off
FY14	
FY15	October: **Alpha Build** 1.0.0 release and website launch March: 2.0.0 release July: 3.0.0 release
FY16	October: **Beta Build** 4.0.0 release and users conference December: 5.0.0 release March: 5.1.0 release *We are here* Summer: planned **Release Candidate** 6.0.0 • System updates • Serialization, modularity, and optimization
FY17	Several releases throughout • New systems/features
FY18	October: **Final Contractual** release Maintenance only

Current Collaborators and Integrators

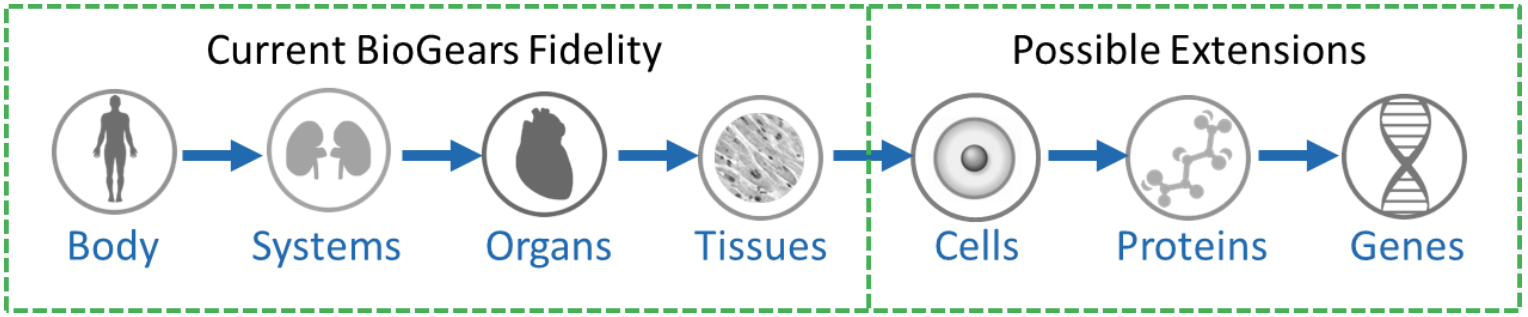
- 2,700+ downloads of the engine and related files since the Alpha Build Release (October 2014)
- 1,400+ pages of physiology modeling methodology and software documentation, and validation data available to our user community
- Used by the government/military, academic institutions, and commercial businesses
- Let us know if/when you use BioGears and we can add you to the home page of our website!

MODELING APPROACH

Engine Overview

Modeling Approach:

- Top-down approach to model development with bottom-up hooks for engine expansion
- Multi-scale for varying fidelity, allowing integration of models from any level



Computation Approach:

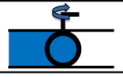
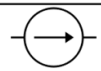
- Time-stepping transient analysis for linearization of differential equations
  - Currently 90Hz for 2x real-time simulation on standard laptops
- Dynamically change/add/remove elements to represent physiological mechanisms
- Stabilization analysis for initialization and implementation of conditions
- Designed with low computational overhead
  - Faster than real-time on typical PC, multiple instances on single or multicore processors
  - Build Targets include Windows, Mac, Linux, and Raspberry Pi

Background: Lumped Parameter Modeling

- Discrete entities that approximate the behavior of a distributed system
- Electronic-Hydraulic/Thermal Analogy: body system fluid dynamics and thermodynamics modeled using electrical circuit math
- Generalized definitions of Nodes, Paths, and Elements for simple understanding, implementation, and modification

Lumped Parameter Modeling of Fluids

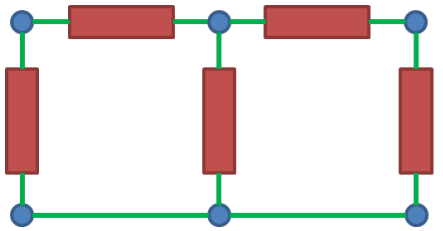
P=Pressure, F=Flow, R=Resistance, C=Compliance, I=Inertance

Element	Circuit Analogy		Pipe Analogy		Flow Equation
Node	Junction		Junction		Total Flow = 0
Path	Wire		Rigid Pipe		Solve Directly
Resistance	Resistor		Aperture		$F = P/R$
Compliance	Capacitor		Diaphram		$F(t) = C\frac{dP(t)}{dt}$
Inertance	Inductor		Heavy Paddle		$F = \frac{1}{L}\int_{t_0}^{t} P\,dt + F(t_0)$
Switch	Switch		Gate Valve		Solve Directly
Valve	Diode		Check Valve		Solve Directly
Pressure Source	Voltage Source		Pump		Solve Directly
Flow Source	Current Source				$F = F$

Lumped Parameter Approach

- Data model
  - Generic and reusable node and path definitions
  - Uses the same equations/code with native units
- Other element types not in table:
  - Switch
  - Valve/diode
  - Polarized elements

Definitions

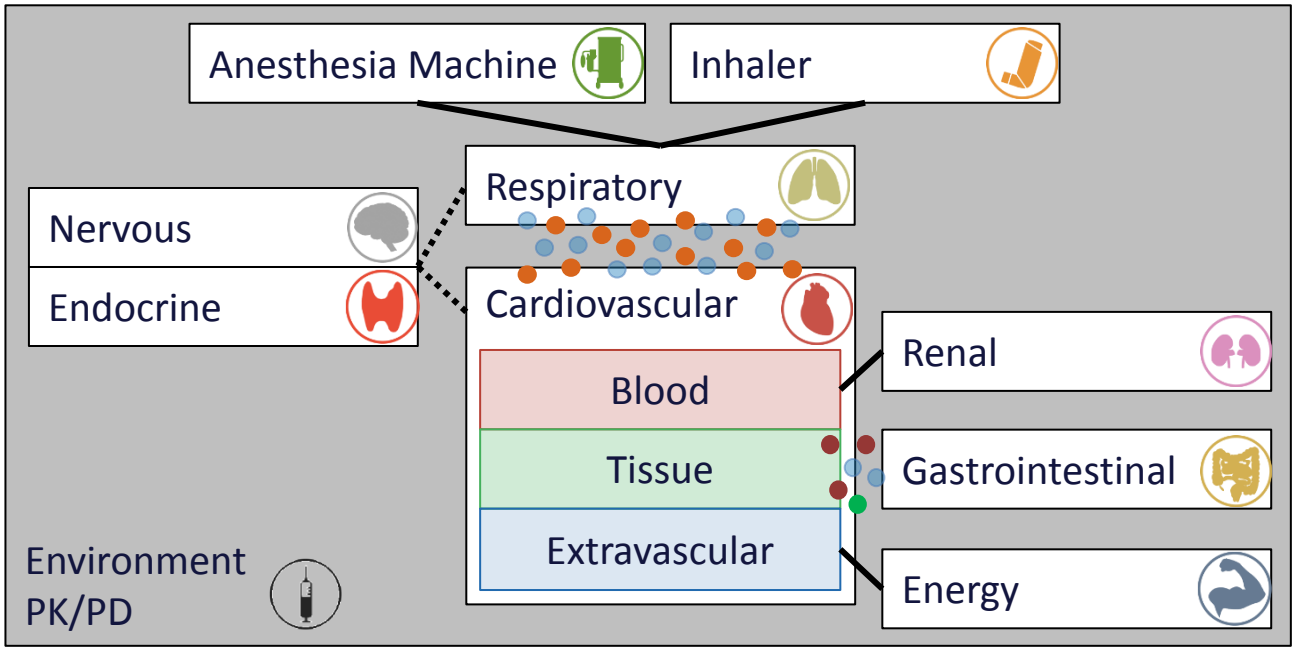


Circuit Types and Elements

		Description	BioGears Included				Other Possible Extensions		
			Generic	Electrical	Fluid	Thermal	Translational	Rotational	Concentrational
Variables	Primary	Across	Potential	Voltage	Pressure	Temperature	Velocity	Angular Velocity	Concentration
		Through	Flux	Current	Flow	Heat Flow	Force	Torque	Flow
	Integrated	∫(Across)·dt	------	Magnetic Flux	Pressure Momentum	------	Displacement	Angular Displacement	------
		∫(Through)·dt	Quantity	Charge	Volume	Heat	Momentum	Angular Momentum	Quantity
Elements	Passive	Resistor	Resistance	Resistance	Resistance	Resistance	Damping	Damping	Clearance
		Capacitor	Capacitance	Capacitance	Compliance	Capacitance	Mass	Inertia	Capacitance
		Inductor	Inductance	Inductance	Inertance	Inductance	Stiffness	Torsional Stiffness	------
	Source	Across Source	Potential Source	Voltage Source	Pressure Source	Temperature Source	Velocity Source	Angular Velocity Source	Concentration Source
		Through Source	Flux Source	Current Source	Flow Source	Heat Flow Source	Force Source	Torque Source	Flow source

Key: In the CDM

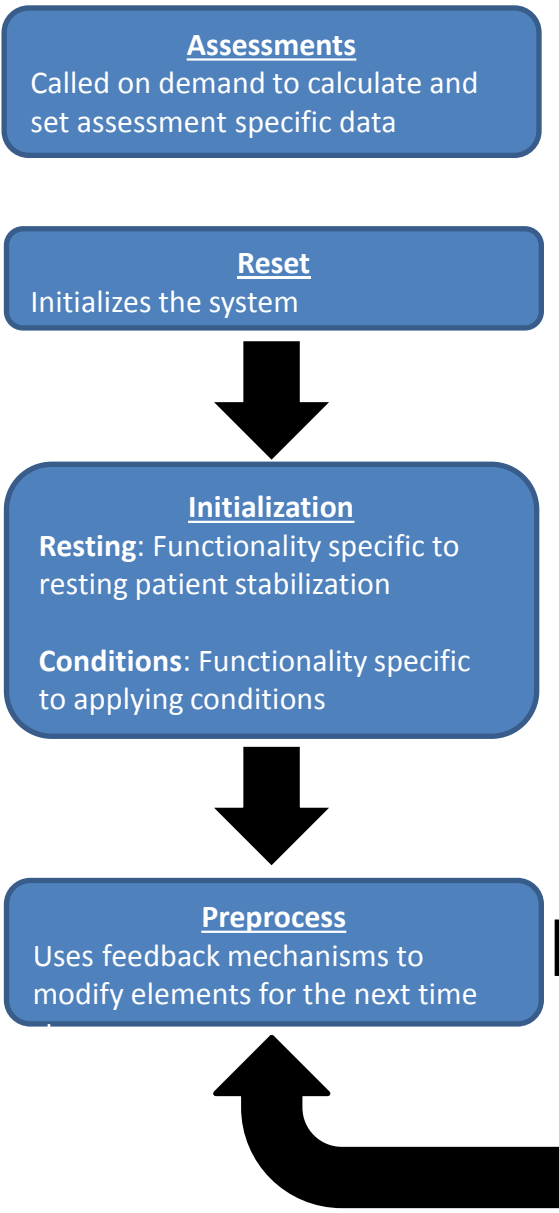
Physiology System Interaction



Connection types:

- Direct circuit connection – e.g. Anesthesia Machine and Respiratory
- Feedback – e.g. Nervous and Endocrine
- Substance exchange – e.g. Respiratory and Cardiovascular gas exchange

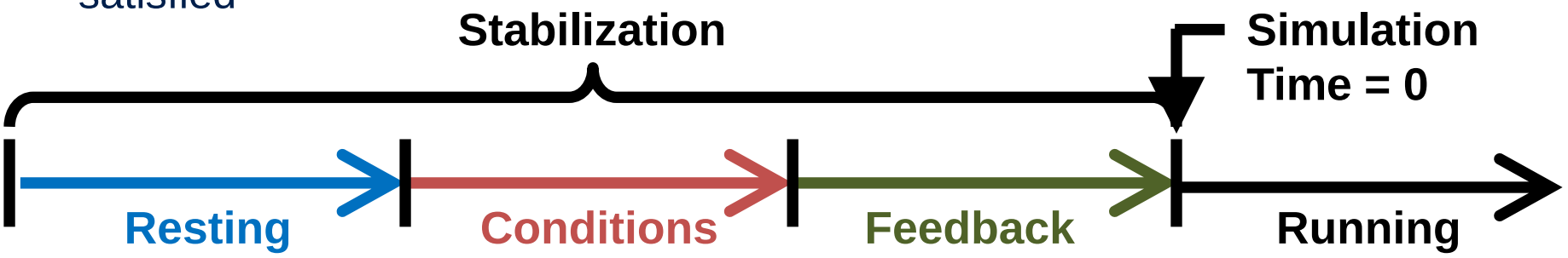
System Data Flow and Modeling Approach Advantages



- Modular and extensible
- Model fidelity easily modified by adding/removing nodes and elements to circuit
- Fully dynamic physics based mechanistic models (rather than state based) – cascading effects
- Unlimited stacking/combining of conditions, insults, interventions, interfaces, etc.
- Homeostasis based modeling with pathophysiology actions
- Able to integrate existing/new models
  - Not necessarily lumped parameter
  - Mixed fidelity
- Able to simultaneously run any number of instances/patients

Engine Initialization

- Dynamic stabilization drives towards patient homeostasis
- Each step the engine executes until all specified stabilization criteria are satisfied



Step 1: Patient initialization
- Systems feedback modifies values to achieve specified patient parameters (e.g. baseline mean arterial pressure)
- Standard environment used

Step 2: Condition initialization
- Conditions applied to represent new patient homeostatic state
- Environment changes applied to simulate long term acclimation

Step 3: Feedback Mechanisms
- Feedback mechanisms that would interfere with chronic conditions (e.g. baroreceptors) are activated

Simulation begins
- Acute insults, interventions, and parameter modification applied instantaneously through actions

Engine Data Library

Patients
- Properties modify system setup, circuit values, and feedback parameters

Substances
- Physical and transport related properties
- E.g. *MolarMass, IonicState, Sedation*

Compounds
- Concentrations of multiple substances
- E.g. *Saline, Blood*

Environments
- Surrounding properties
- E.g. *AmbientTemperature, ClothingResistance*

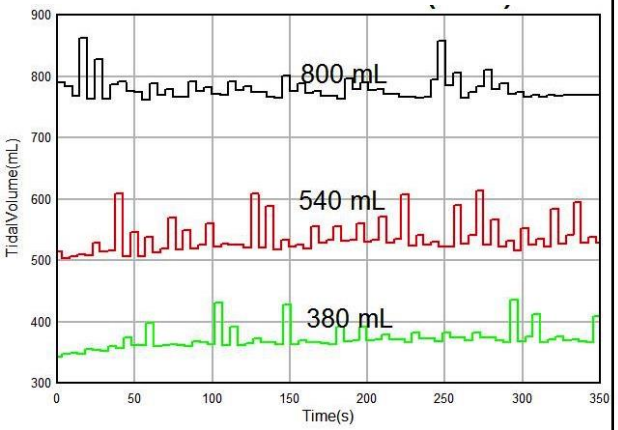
Nutrition
- Meal composition (masses)
- E.g. *Protein, Calcium*

Stabilization
- Percent difference criteria for stabilization – resting and conditions

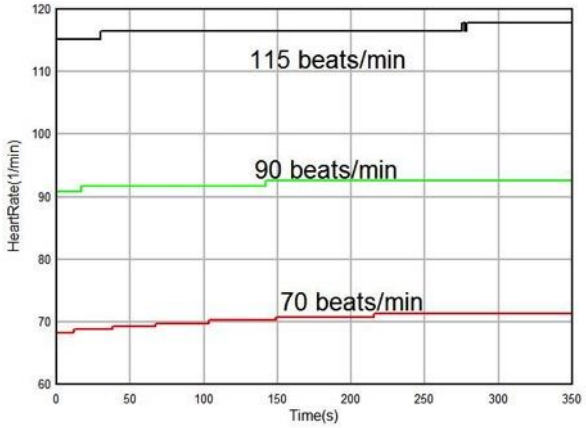
Patient Modification Example

Patient File Parameters	
Gender	FunctionalResidualCapacity
Age	**2**: HeartRateBasline
1: Weight	**3**: MeanArterialPressureBaseline
Height	RespirationRateBaseline
BodyFatFraction	RightLungRatio
CarinaToTeethDistance	TotalBloodVolumeBaseline
Contractility	

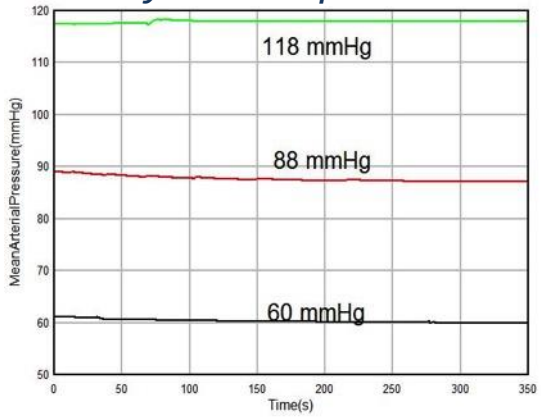
1 *Tidal Volume varies with weight*



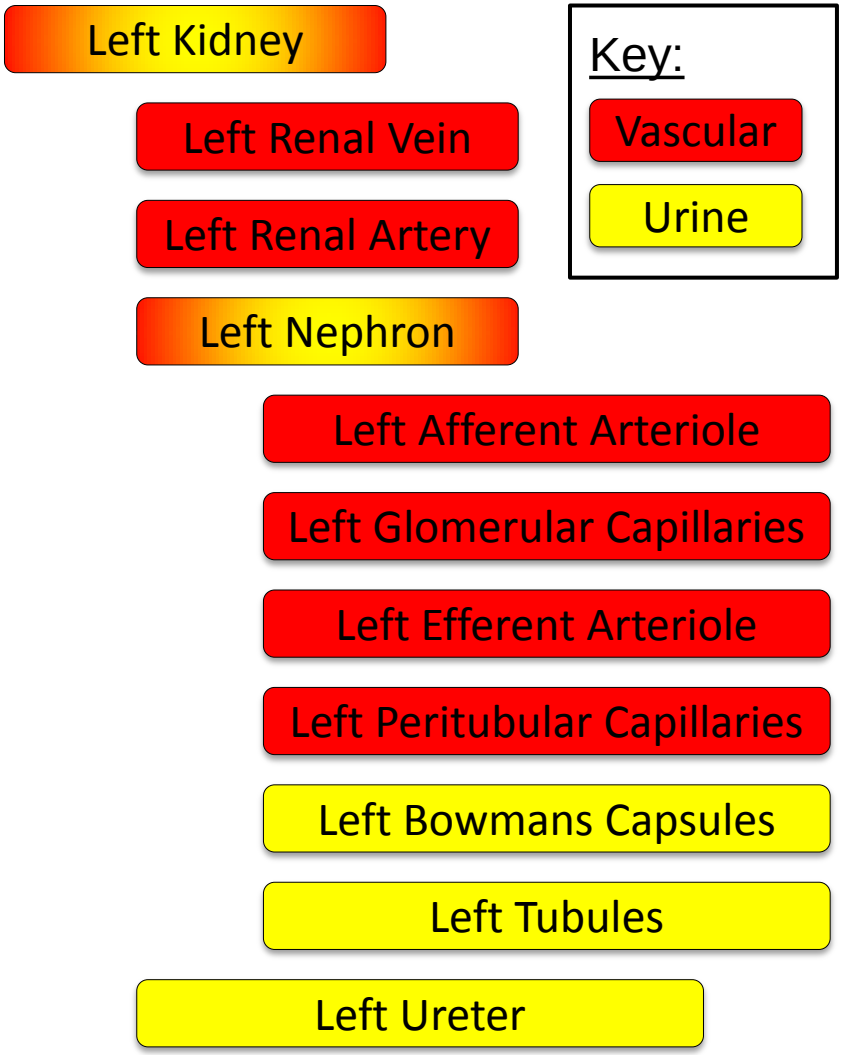
2 *Driver is modified to vary heart rate*



3 *Circuit is modified to vary arterial pressure*



Compartment Example: Kidney Definition



- Anatomical Compartments defined by sub-circuits and allow access via an anatomy tree
- Several overlapping compartment types
  - Fluid
    - Liquid
      - Vascular
      - Urine
      - Chyme
    - Gas
      - Pulmonary
  - Tissue
  - Thermal
  - Electrical
- Compartment **properties** are combined from children (liquid example)
  - **Volume** is a sum
  - **InFlow** is a sum
  - **OutFlow** is a sum
  - **Pressure** comes from an assigned child node (sum does not make sense)
- **Substance quantities** (mass, concentration, etc.) are calculated on demand for any level in hierarchy
- There are thousands of compartment data values that are updated each time-step

VERIFICATION AND VALIDATION

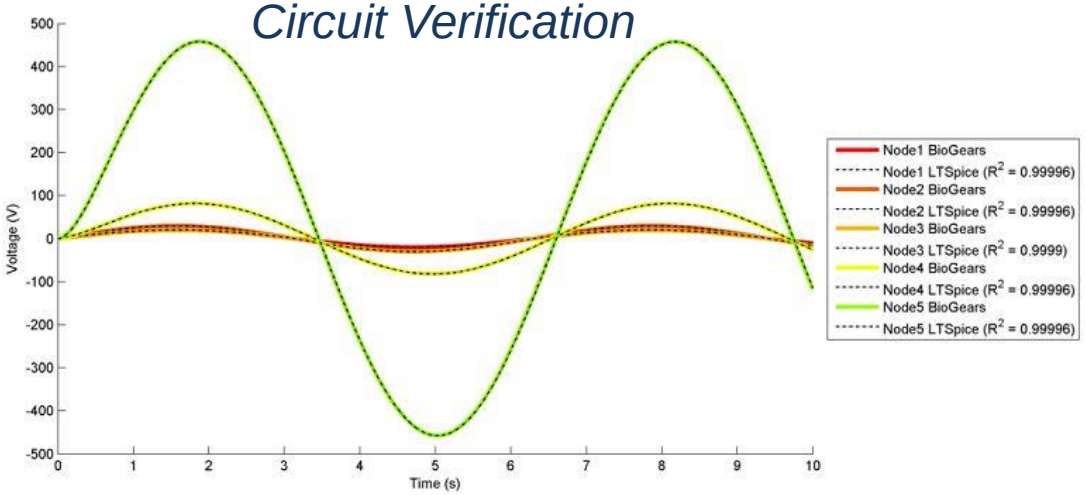
Verification

1. **Full Scenario Suite:** BioGears test suite includes scenarios to test all patient files, patient actions, substance effects, and equipment performance. Completed for 3 circuit unit tests and 80+ scenarios.
2. **Circuit Verification:** Verify that the BioGears circuit solver is producing comparable results to established circuit solvers. Completed for 100+ circuit elements/combinations.
3. **Timing:** Suite is executed by team members throughout development. It is also automatically executed when the code base is altered in the repository.
4. **Output:** Each scenario indicates the physiologic outputs for validation. Each output is tested to ensure it is within 2% of the results in the code repository. Comparison and error plots (shown) are generated.
5. **Full Results:** An email is sent to all team members when verification is complete. Each scenario either Passes (green) or Fails (red). Failures must be addressed by the team.

VentilatorPressureLossScenarioResultsReport	1	1	21.258999824523926
YpieceDisconnectScenarioResultsReport	1	1	23.98900008201599
AirwayInsultObstructionResultsReport	0	1	14.930999994277954
AtropineScenarioResultsReport	0	1	13.121000051498413
BasicScenario1ResultsReport	0	1	18.195000171661377

Scenario Verification

Circuit Verification



Calibration and Validation

1. **Verification:** Unit tests ensure correct implementation and sound physics principles for all tools
2. **System Level Validation:** All major systems (cardiovascular, respiratory, blood chemistry, etc.) are validated for clinical output level data
3. **Compartment Level Calibration:** Individual organs (kidney, liver, etc.) or functional units (trachea, alveoli, etc.) are validated wherever possible
4. **Scenario Calibration & Validation:** Every insult, intervention, and assessment includes a matrix with validation data for whole body combined effects from multiple systems
5. **Combined Scenario Validation:** All four showcases and several other scenarios validated for combined effects – heavily leveraged SME consultants Bryan Bergeron MD and Nicholas Moss PhD

Showcase Scenario Combined Effects Validation

Scenario	Number (%) of Validation Measures in Deviation Category			Total
	< 10%	10 – 30%	> 30%	
Combat Multitrauma	59 (64.8%)	10 (11.0%)	22 (24.2%)	91
Asthma Attack	26 (65.0%)	7 (17.5%)	7 (17.5%)	40
Heat Stroke	52 (76.5%)	10 (14.7%)	6 (8.8%)	68
Exposure	26 (86.7%)	2 (6.7%)	2 (6.7%)	30

SYSTEMS REVIEW

Cardiovascular

Feedback
- Heart driver – variable compliance

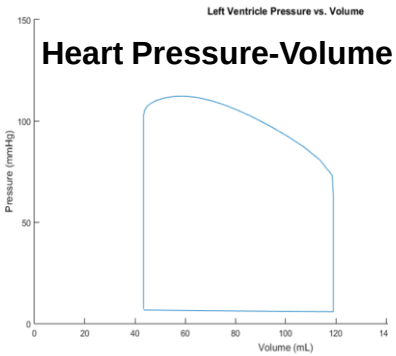
Actions
- Cardiac Arrest
- CPR
- Hemorrhage
- Pericardial Effusion

Conditions
- Anemia
- Arrhythmia
- Bradycardia
- Tachycardia
- Heart Failure
- Pericardial Effusion

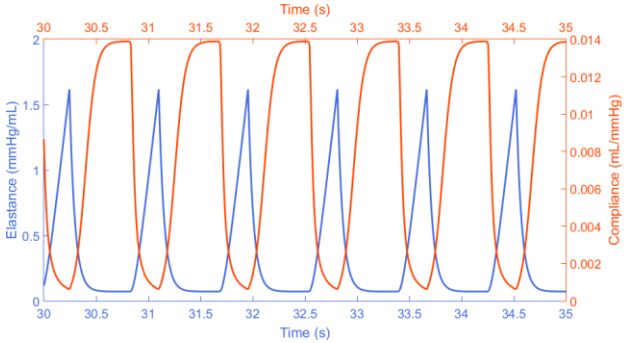
Events
- Asystole
- Bradycardia & Tachycardia
- Cardiac Arrest
- Hypovolemic Shock

Assessments
- None

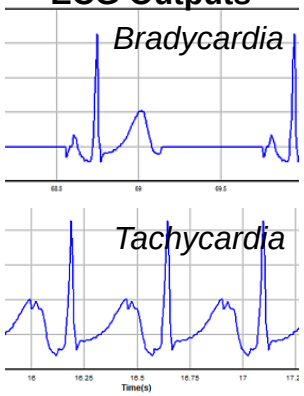
Heart Pressure-Volume Curve



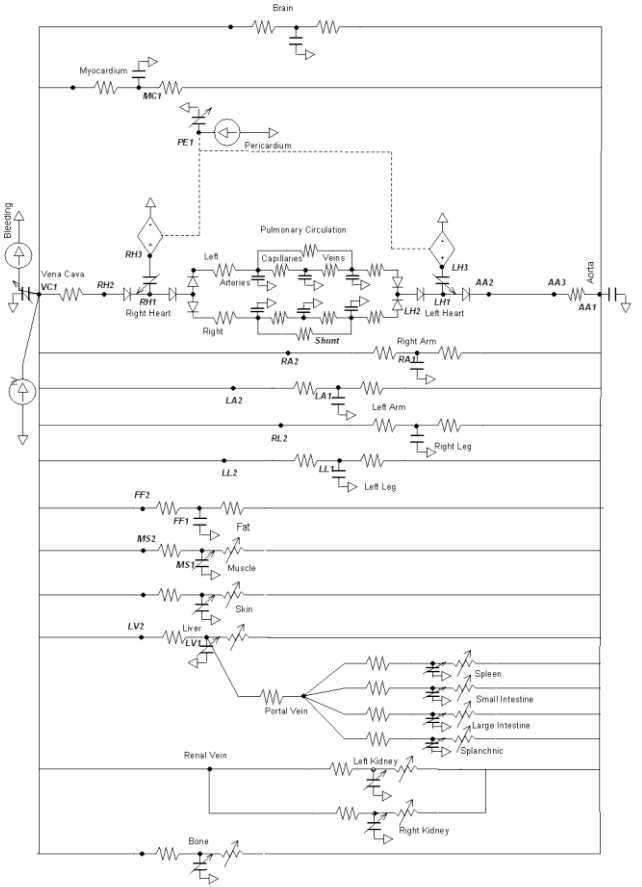
Heart Elastance and Compliance



ECG Outputs



Circuit Diagram



Resting Validation

Data Type	Number (%) of Validation Measures in Deviation Category			Total
	< 10%	10 – 30%	> 30%	
System	18 (75.0%)	4 (16.7%)	2 (8.3%)	24
Compartment	54 (84.4%)	4 (6.3%)	6 (9.4%)	64

Respiratory

Feedback
- Respiratory driver – from aorta O2 and CO2
- Pleural compliance – from lung volume

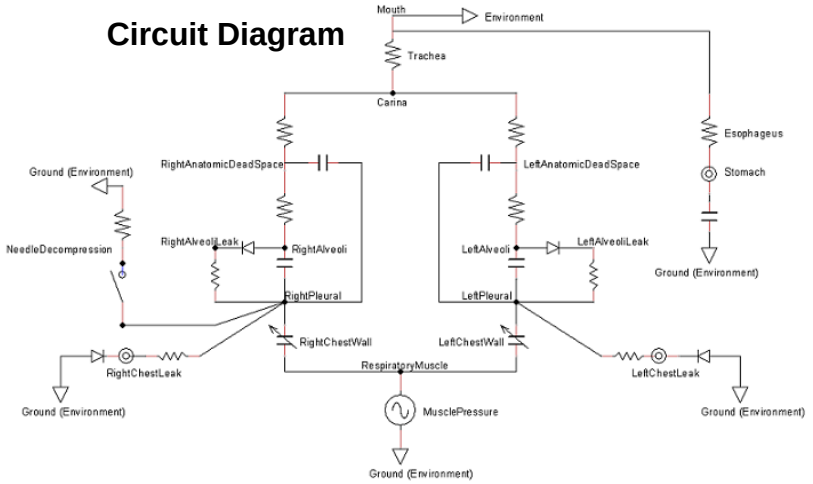
Actions
- Airway Obstruction
- Bronchoconstriction
- Asthma Attack
- COPD Bronchitis
- Intubation
- Pneumothorax
- Conscious Respiration
- Occlusive Dressing
- Needle Decompression

Conditions
- COPD (Bronchitis and Emphysema)
- Lobar Pneumonia
- Respiratory Acidosis & Alkalosis
- Max Pulmonary Ventilation Rate
- Right Mainstem Intubation

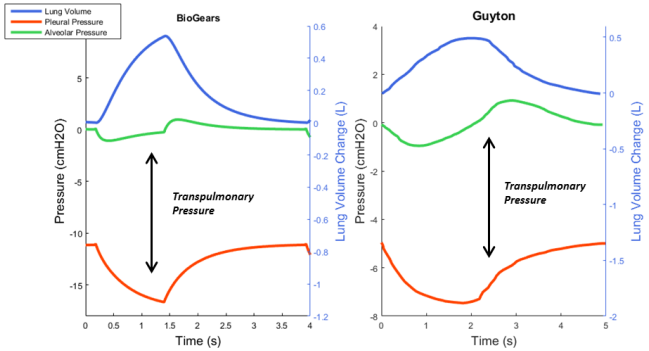
Events
- Bradypnea & Tachypnea

Assessments
- Pulmonary Function Test

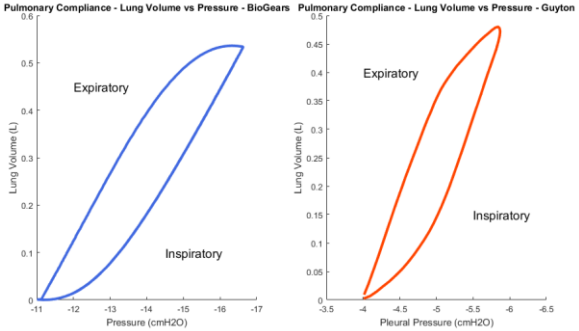
Circuit Diagram



Lung Volume and Pressures vs Accepted



Variable Compliance vs Accepted



Resting Validation

Data Type	Number (%) of Validation Measures in Deviation Category			Total
	< 10%	10 – 30%	> 30%	
System	10 (83.3%)	0 (0.0%)	2 (16.7%)	12
Compartment	31 (86.1%)	2 (5.6%)	3 (8.3%)	36

Renal

Feedback
- Ultrafiltration – from substance molecular weight/radius and charge
- Colloid osmotic pressure – from local Albumin concentration
- Tubuloglomerular – from tubules sodium delivery
- Osmoreceptor – from blood osmolarity
- Active and Passive Reabsorption – from ratio to fluid flow
- Gluconeogenesis
- Drug clearance

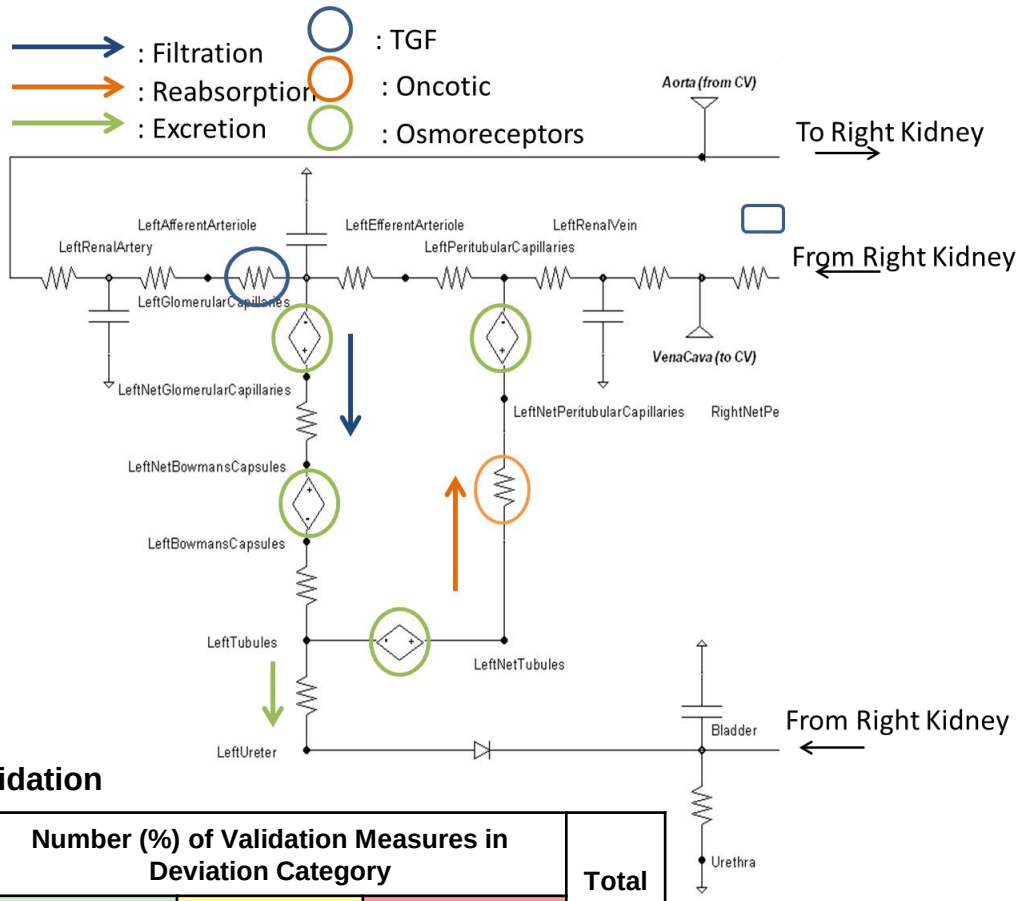
Actions
- Urinate

Conditions
- Renal Stenosis

Events
- Diuresis & Antidiuresis
- Natriuresis
- Dehydration
- Functional Incontinence

Assessments
- Urinalysis

Left Kidney Circuit Diagram



Resting Validation

Data Type	Number (%) of Validation Measures in Deviation Category			Total
	< 10%	10 – 30%	> 30%	
System	28 (56.0%)	7 (14.0%)	15 (30.0%)	50
Compartment	25 (55.6%)	12 (26.7%)	8 (17.8%)	45
Substance Params	15 (50.0%)	6 (20.0%)	9 (30.0%)	30
Assessment	6 (100.0%)	0 (0.0%)	0 (0.0%)	6

Environment

Settings
- Air Density
- Air Velocity
- Ambient Temperature
- Atmospheric Pressure
- Clothing Resistance
- Emissivity
- Mean Radiant Temperature
- Relative Humidity
- Respiration Ambient Temperature
- Ambient Substance

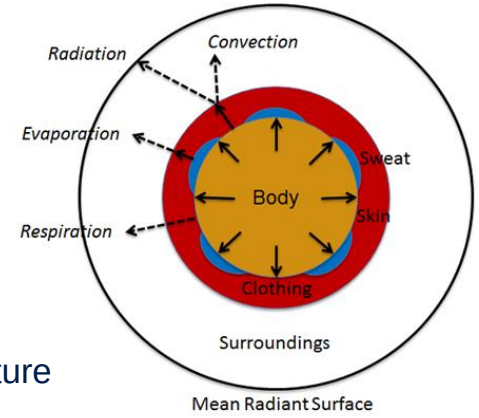
Actions
- Environment Change
- Thermal Application
  - Active Heating
  - Active Cooling
  - Applied Temperature

Conditions
- Environment Change

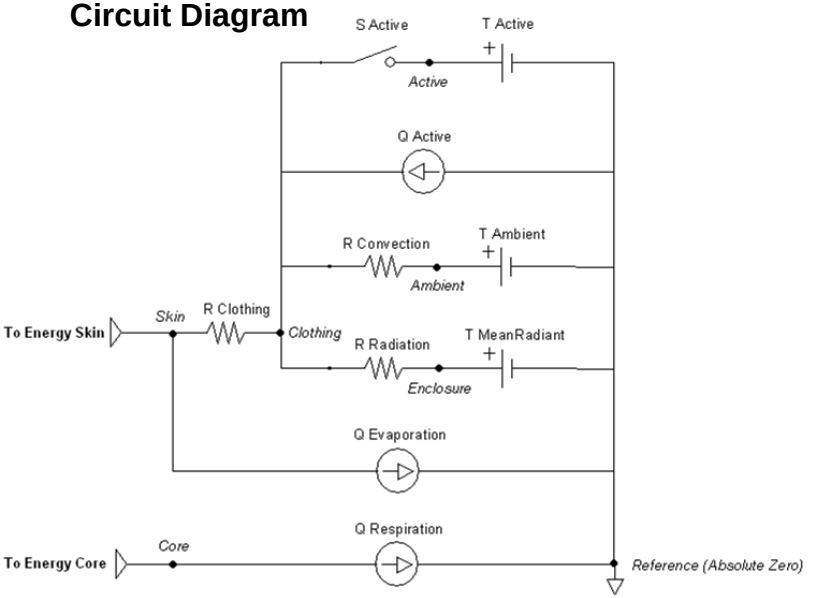
Events
- None

Assessments
- None

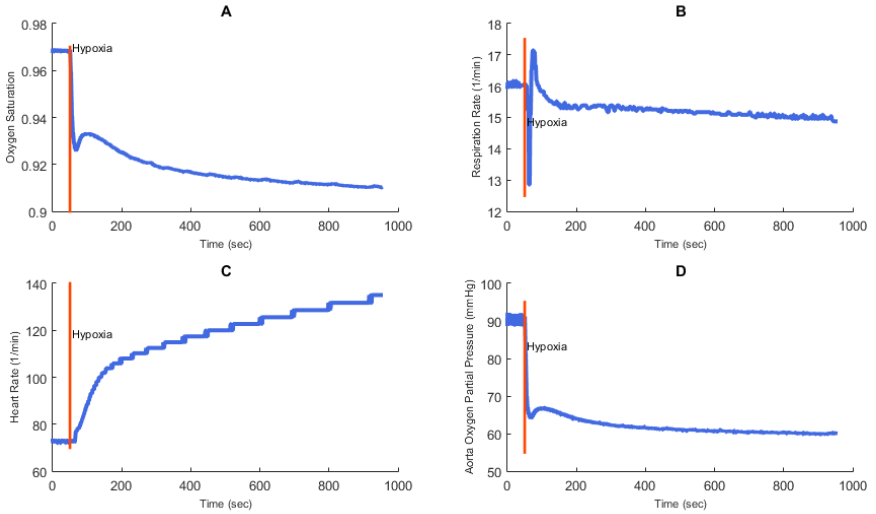
Thermoregulation Model



Circuit Diagram



High Altitude Change Scenario Results



Energy

Feedback
- Thermal feedback on vascular resistance
- Sweating response due to increase core temperature
- Shivering response due to decreased core temperature
- Metabolic effects on Cardiovascular and Respiratory systems during physical activity

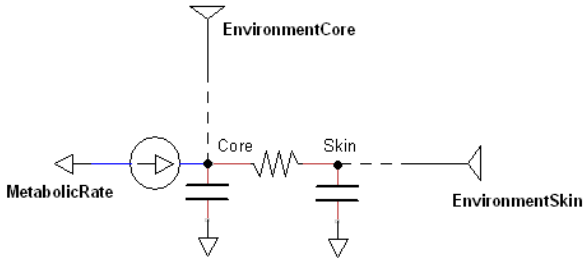
Actions
- Exercise

Conditions
- Dehydration
- Starvation

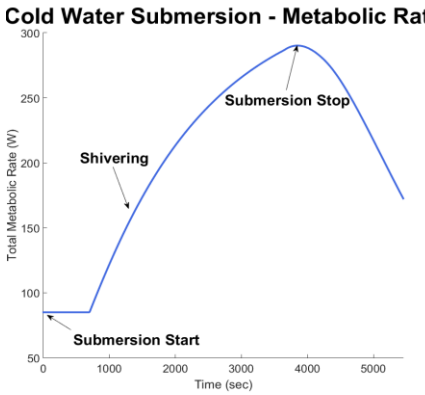
Events
- Fasciculation
- Fatigue
- Hyperthermia
- Heat Stroke
- Metabolic/Respiratory Acidosis & Alkalosis

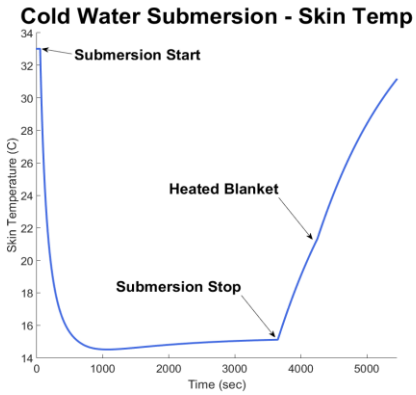
Assessments
- None

Circuit Diagram

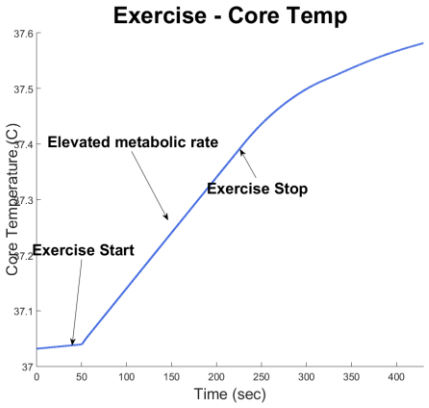


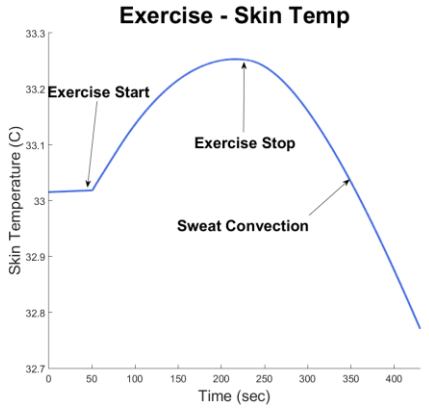
Cold Water Submersion Scenario Results





Exercise Submersion Scenario Results





Resting Validation

Data Type	Number (%) of Validation Measures in Deviation Category			Total
	< 10%	10 – 30%	> 30%	
System	9 (100.0%)	0 (0.0%)	0 (0.0%)	9

Drugs

Feedback
- PK
  - Partition Coefficients
  - Clearance
- PD
  - Drug Effects

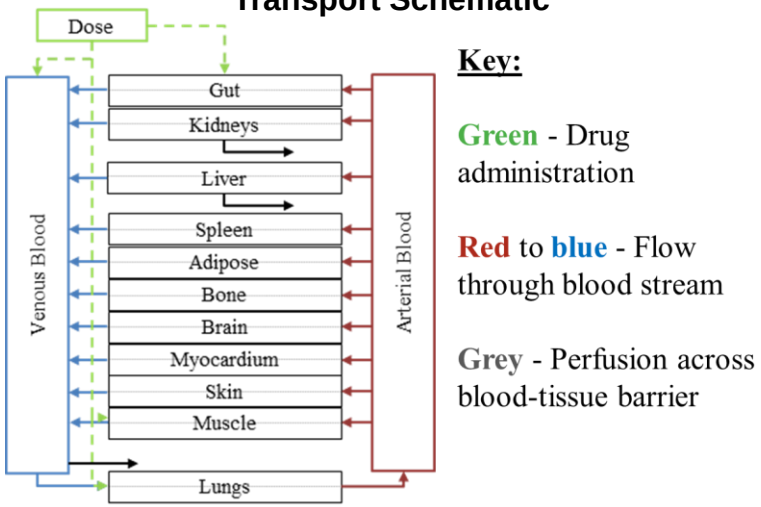
Actions
- IV Fluid Administration
- IV Drug Administration
- IM Drug Administration

Conditions
- None

Events
- None

Assessments
- None

Transport Schematic



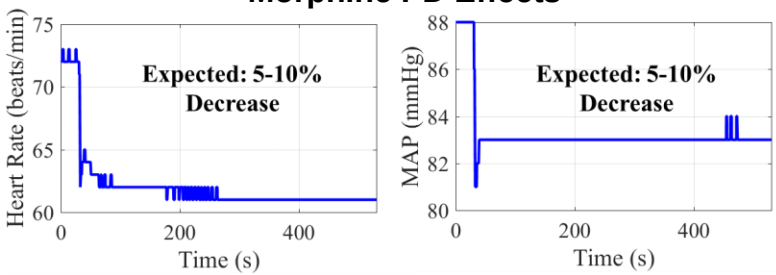
Key:

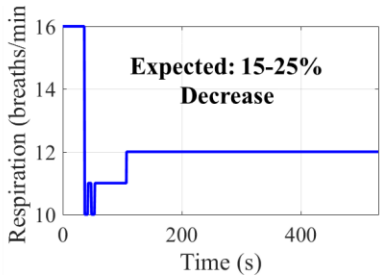
Green - Drug administration

Red to **blue** - Flow through blood stream

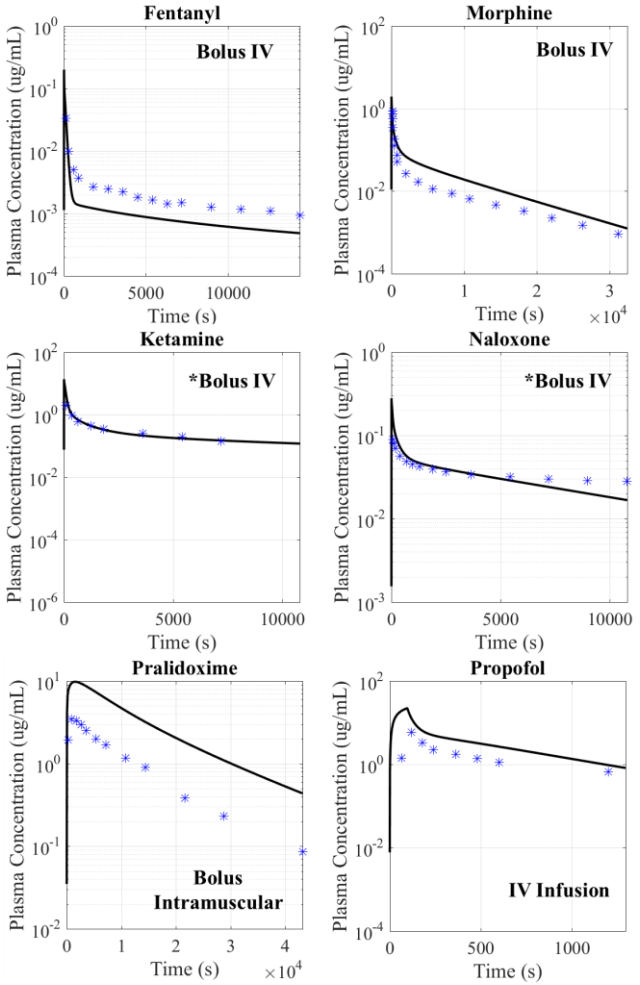
Grey - Perfusion across blood-tissue barrier

Morphine PD Effects





PK Validation



Anesthesia Machine

Settings

- General
  - State (on/off)
  - Ventilator Pressure
  - Respiratory Rate
  - Positive End Expired Pressure
  - Inspiratory Expiratory Ratio
  - Relief Valve Pressure
  - Ventilator Pressure
  - Oxygen Bottle One Volume
  - Oxygen Bottle Two Volume
- Gas Inlet Settings
  - Inlet Flow
  - Oxygen Fraction
  - Primary Gas (Nitrogen/Air)
  - Oxygen Source (Bottle 1/Bottle 2/Wall)
- Related Settings
  - Airway Mode (Free/Mask/Tube)
  - Substance Administration

Actions

- Expiratory/Inspiratory Valve Leaks/Obstructions
- Soda Lime Failure
- Mask/Tube Leak
- Vaporizer Failure
- Ventilator Pressure Loss
- Oxygen Port/Tank Pressure Loss
- Endotracheal Intubation
- Esophageal Intubation

Conditions

- Environment Change

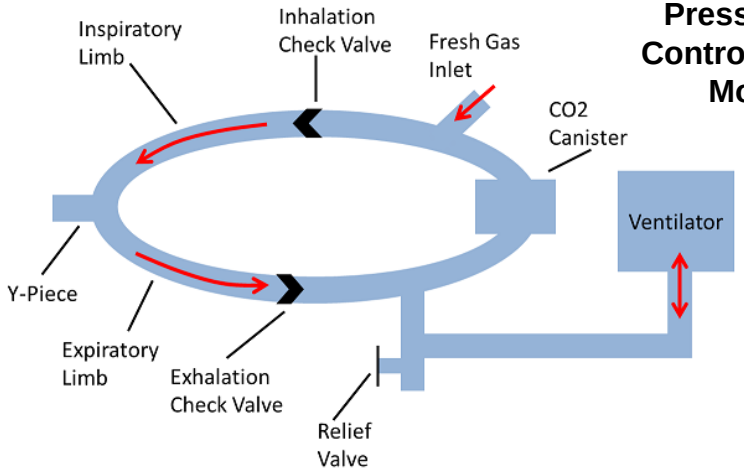
Events

- Oxygen Bottle Exhausted
- Relief Valve Active

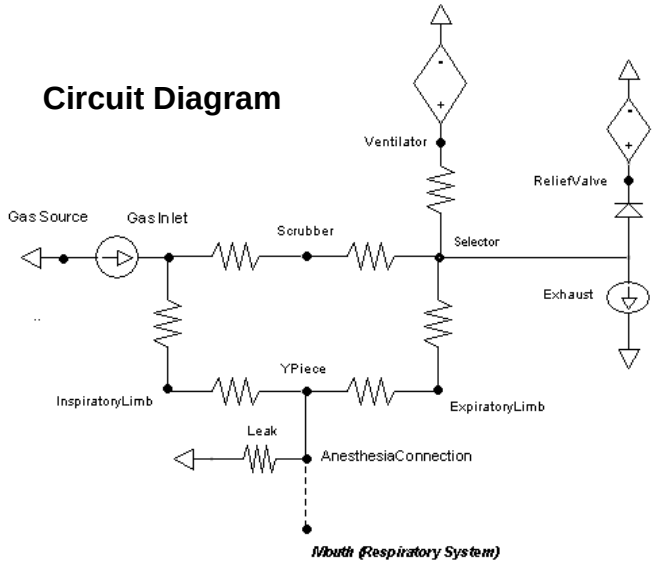
Assessments

- None

Pressure Controlled Model



Circuit Diagram



Inhaler

Settings
- Substance
- Metered Dose
- Nozzle Loss
- Spacer Volume

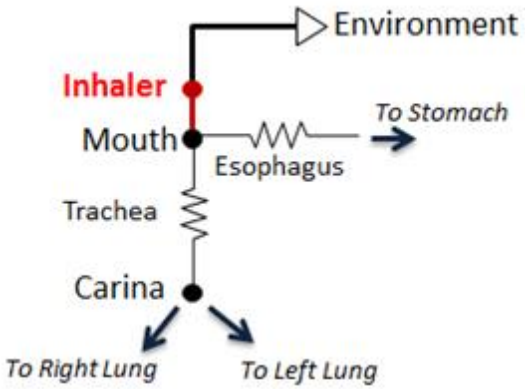
Actions
- Actuation

Conditions
- None

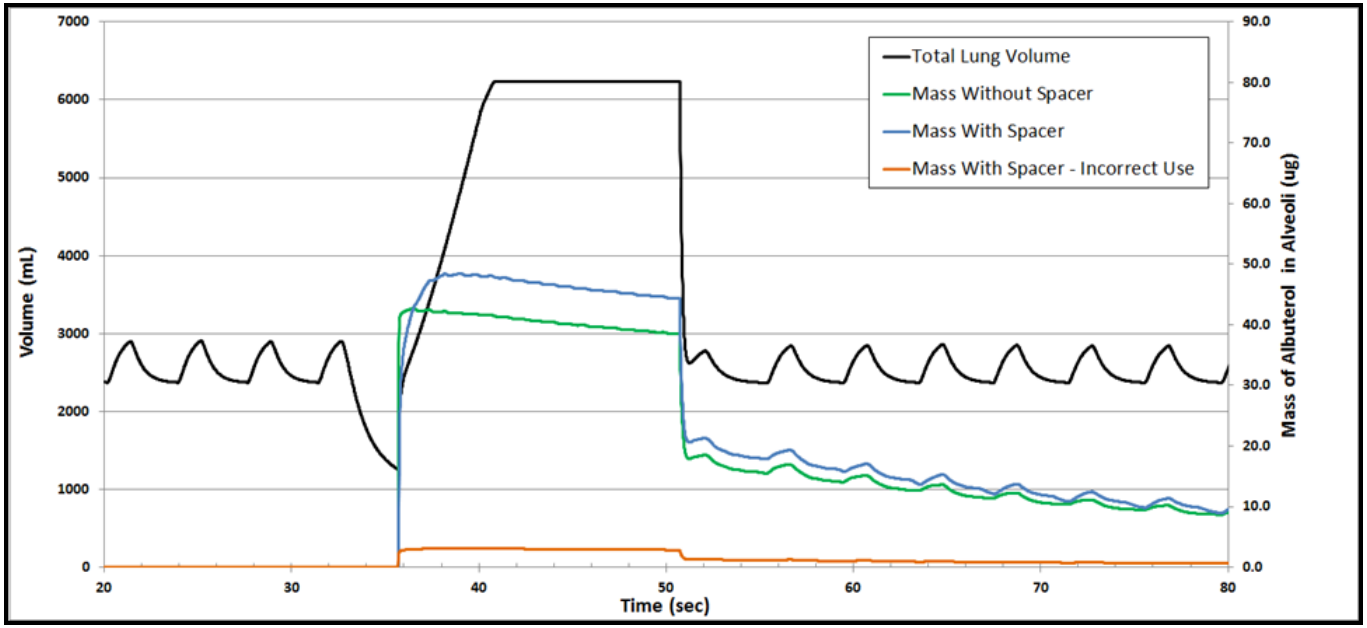
Events
- None

Assessments
- None

Circuit Diagram



Albuterol Administration Results



Remaining Systems

Feedback
- Baroreceptors [Nervous]
- Epinephrine and Norepinephrine release [Endocrine]
- Produce Albumin [System Interactions / Hepatic]
- Acid-Base balance (including O2 & CO2 saturation & pH) [System Interactions]
- Gas exchange (Alveolar transfer) [System Interactions]

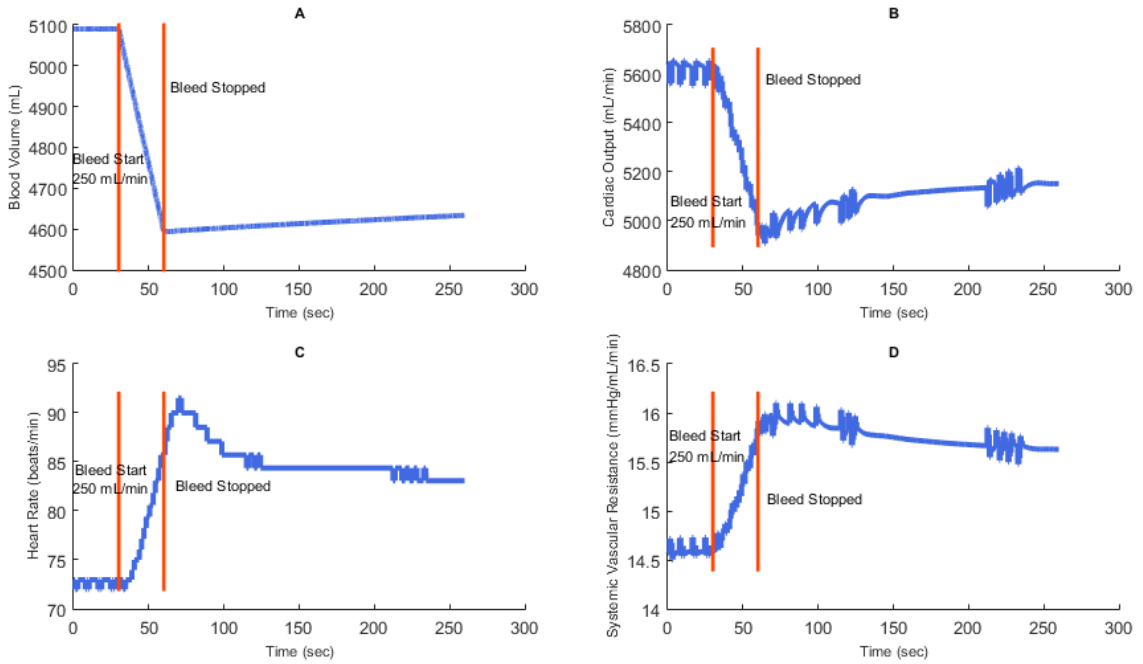
Actions
- Consume Meal [Gastrointestinal]

Conditions
- None

Events
- Irreversible state
- Hypercapnia & Hypoxia [Blood Chemistry]
- Brain & Myocardium Oxygen Deficit [Blood Chemistry]

Assessments
- Complete Blood Count [Blood Chemistry]
- Comprehensive Metabolic Panel [Blood Chemistry]

Hemorrhage Scenario Results



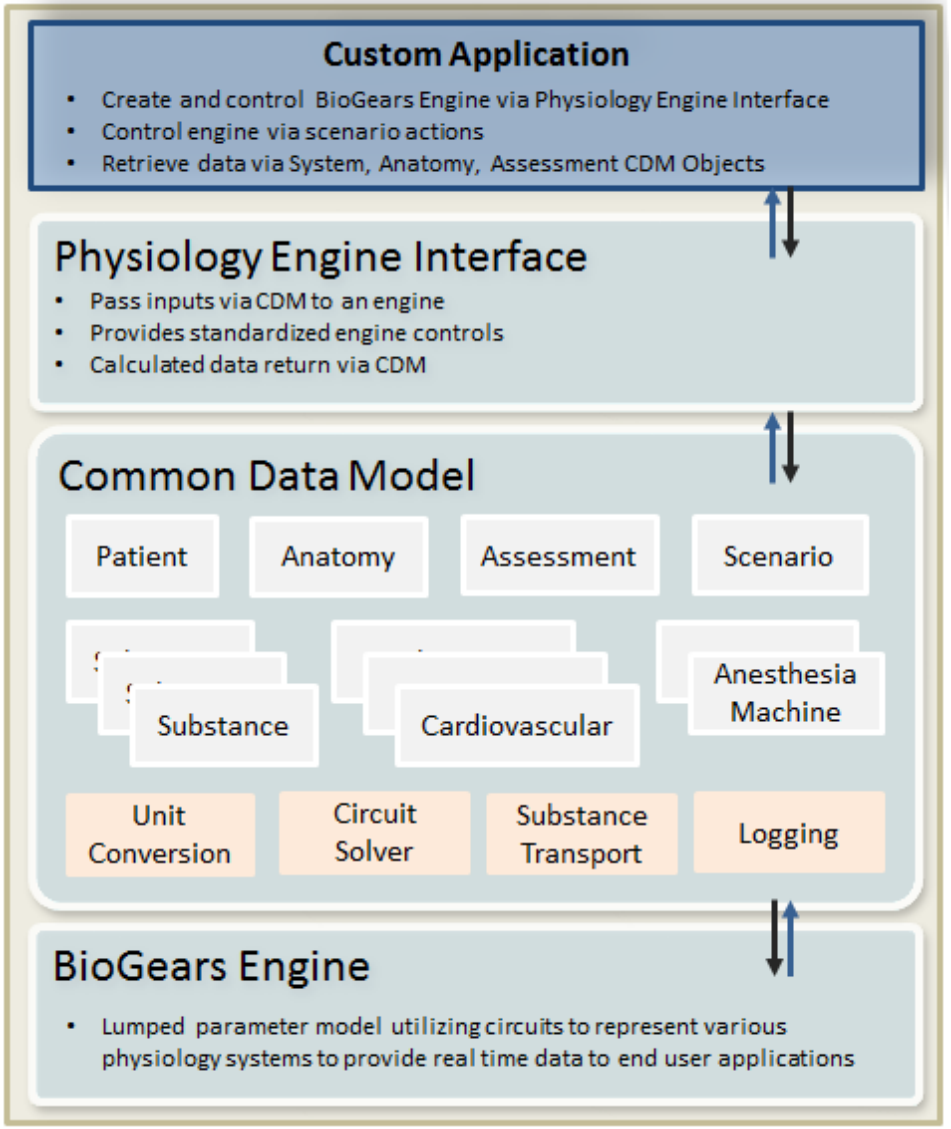
Resting Validation

Data Type	Number (%) of Validation Measures in Deviation Category			Total
	< 10%	10 – 30%	> 30%	
System	37 (84.1%)	2 (4.5%)	5 (11.4%)	44
Patients	85 (100.0%)	0 (0.0%)	0 (0.0%)	85
Assessments	16 (100.0%)	0 (0.0%)	0 (0.0%)	16

ARCHITECTURE AND TOOLS

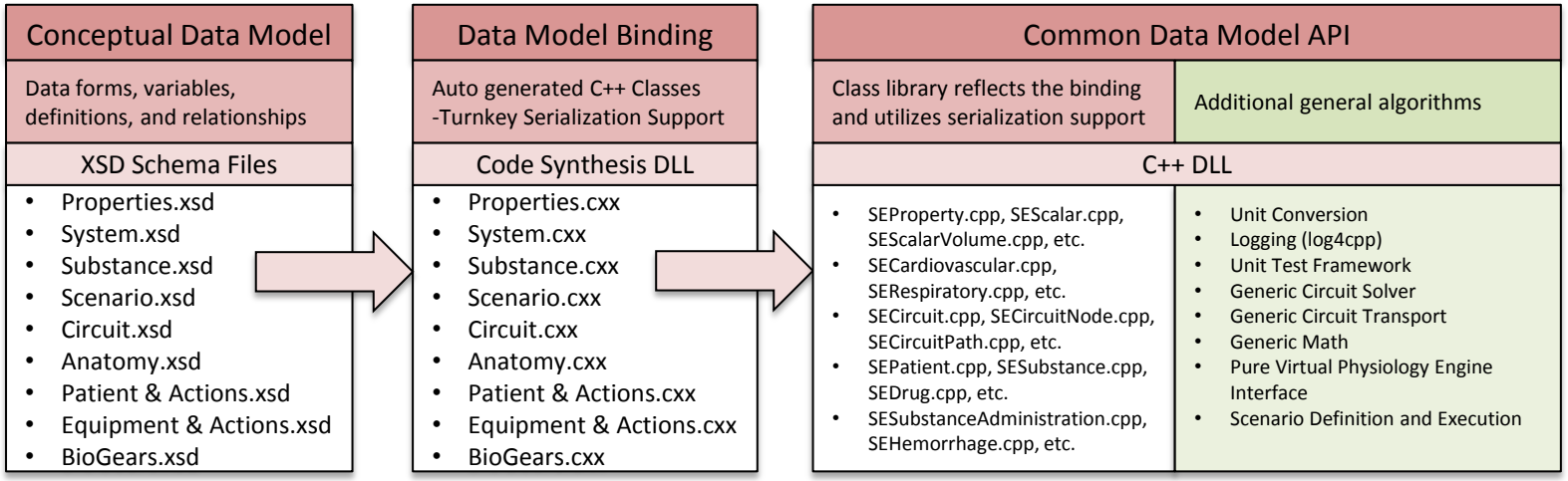
Software Architecture

- ***Common Data Model (CDM)***: Well-defined, intuitive, interchangeable format to standardize interfaces
  - Standardized inputs, outputs, units, and naming conventions to aid model additions and external model integrators
- ***Application Programming Interface (API)***: Easy integration and interaction in any programming language
  - Data organized logically by Anatomy so that users are able to easily find and pull relevant data
- ***Software Development Kit (SDK)***: Application examples and stand-alone execution
  - Tutorials, How-to's, scenario examples



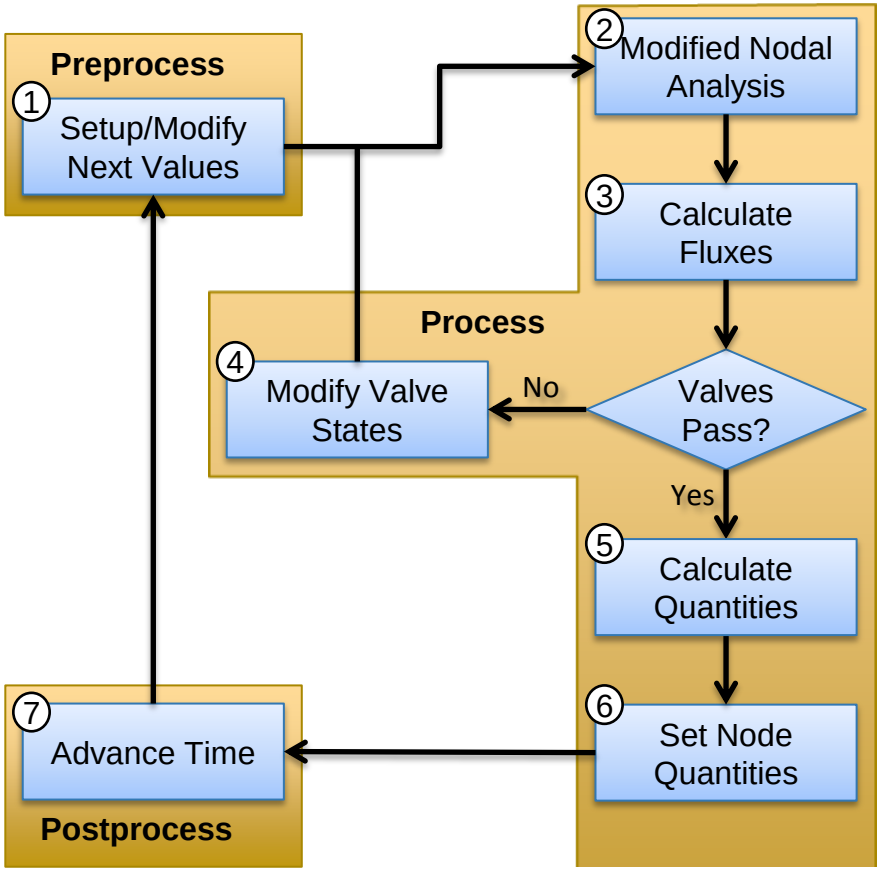
Common Data Model Overview

- Common data structures for modeling and simulation of the human body
  - Not specific to any methodology, including BioGears
- Separates the physiological data from the physiological modeling methodology
- Object Oriented Design of class structures providing a unified set of tools that promotes fast development, compatible data sets, and well-defined interfaces
- Provides a well-defined data interchange format that disparate models can use for standardizing inputs and outputs between each other
  - Allows for specific extensions, but interfaces are defined by the CDM



Circuit Solver

- Fully dynamic Modified Nodal Analysis solver for any valid closed-loop circuit
- Solves circuit types with any units: Electrical, Fluid, Thermal



Preprocess:

1. Systems use "Current" values to setup/modify "Next" values via feedback mechanisms (outside of the solver)

Process:

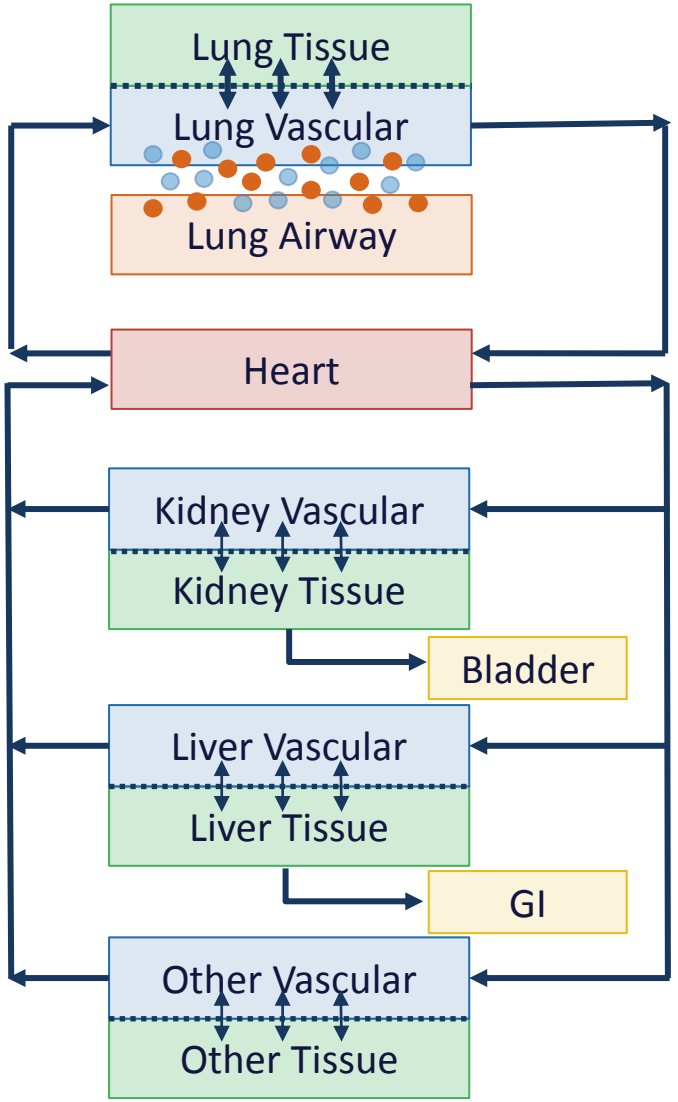
2. Perform numerical integration by using linearization (first order approximations) through Modified Nodal Analysis (Ax=b)
   a. Use KCL (total Flux at each node = 0) to Calculate the Jacobian matrix (A) and right-hand side vector (b) for each Node Potential and Potential Source Flux (x)
   b. Use the Eigen templated library linear solver (FullPivLU) to solve for x vector
3. Calculate unknown Fluxes – using Trapezoid Rule where applicable
4. Calculate Valves using assumed diode states (cannot be solved directly) – iterate as necessary
5. Calculate and increment Compliance Path Quantities – No other elements have dynamic Quantities (rigid pipes)
6. Set Node Quantities (based on Path Quantities)
   - Note: Transporter is called here

Postprocess:

7. Advance time by moving "Next" to "Current" values

Transporter

- Common Data Model:
  - Substances move with the fluid to each node in the circuit
  - No particle deposition
  - Mass is updated as at each time step based on flow into and out of nodes
  - Concentration and partial pressure are updated after the mass
- Systems Interactions:
  - Partial pressure driven diffusion moves substances between two nodes (O_2, CO_2, N_2)
  - Perfusion limited diffusion moves substances across the blood/tissue barrier based on flow and partition coefficients (Drugs)
  - Systemic clearance removes substances from the vena cava to represent metabolic or other clearance mechanisms
  - Hepatic clearance removes substances from the liver to represent the ability of the liver to metabolize or remove substances



Developer GUI

Motivation

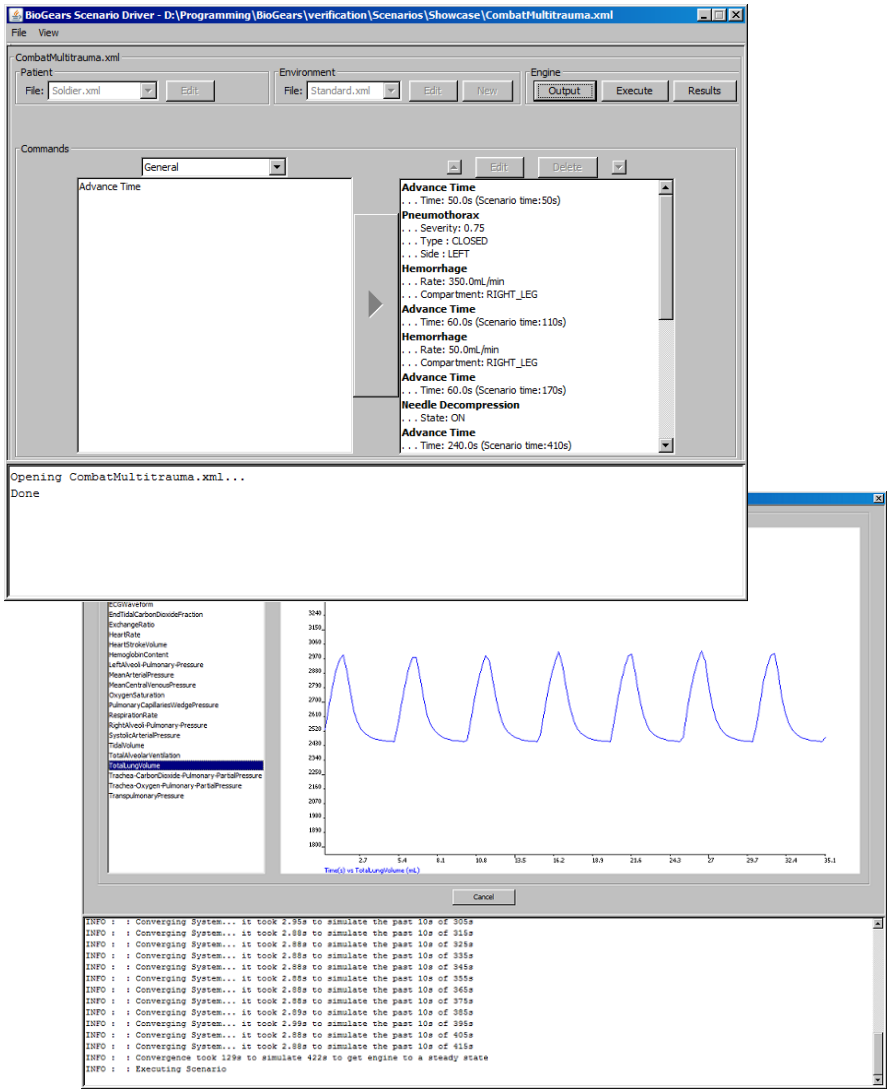
- Data driven developers' tool to demonstrate basic functionality
- Test Engine without command line
- Ready for testing out-of-the-box (no compiling)
- Simple interface for creating, editing, and executing scenario file, and creating resulting plots of requested data

Expectations

- Only requirements are to allow editing and execution of scenarios – not a major focus
- Not heavily QA'ed – some known bugs being continuously fixed

Limitations

- Clunky Java Swing for rapid prototyping via the API



COMING SOON

High Level Near Term Tasks

Current (hopefully deployed this summer with version 6.0.0):

- Bug fixing and system refinement
- Optimization and increased simulation speed
- State serialization – saving and loading simulations
- Modularity – more easily replace entire systems
- Renal feedback updates
- Acid-base balance – O_2 & CO_2 saturation modifications
- Total body substance balance and new substances

Near-Term (FY16):

- Nervous system additions
- Exocrine additions
- Endocrine additions
- Vascular fluid exchange
- Pneumothorax updates
- Gastrointestinal updates

Long-Term (FY17):

- Patient modifications (gender, body mass, etc)
- Intoxications – Ketamine proof of concept
- Airborne agents (Nerve/Pulmonary/Smoke/CO) and vaporization
- Diuretics
- Additions to blood assessments and pulmonary function test improvement

How to Contribute

- Use the software for any and all applications (please let us know)
- Report problems
- Submit code
  - Currently just email us (https://www.biogearsengine.com/workwithus)
  - Moving to a public repository – GitHub/BitBucket hosted
- Post and respond to Forums (https://www.biogearsengine.com/forums)

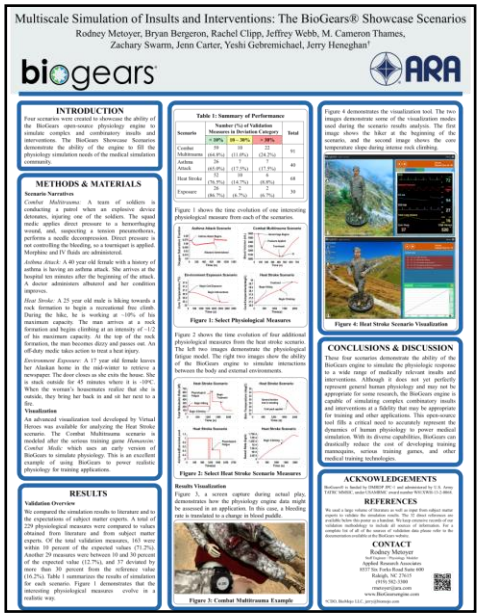
Please Come See Our Posters!

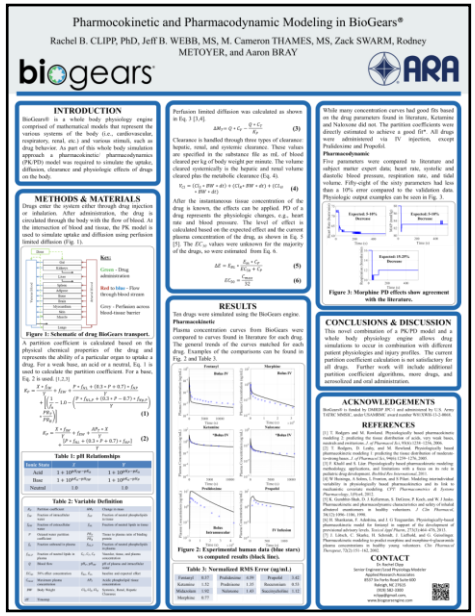
Showcases: Rodney Metoyer

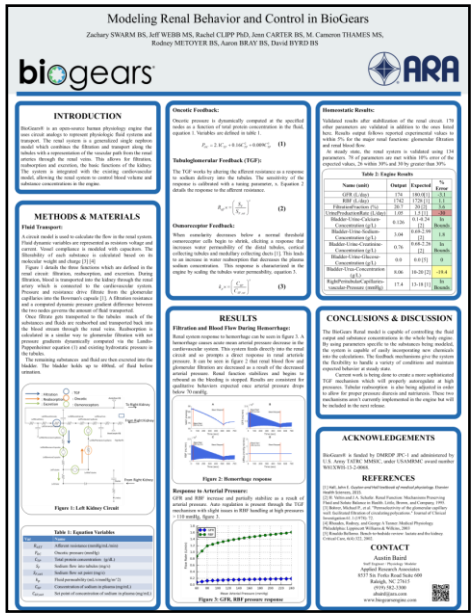
Renal: Dr. Austin Baird

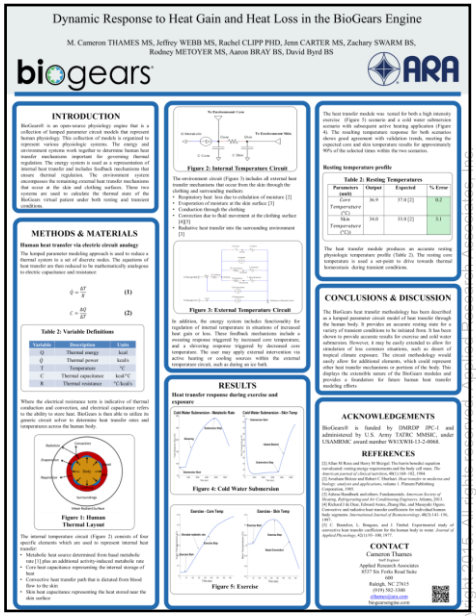
PK/PD: Dr. Rachel Clipp

Energy: Cam Thames









Contact

www.biogearsengine.com/workwithus

Jeff Webb
Principal Investigator
jwebb@ara.com
919-582-3435

Rachel Clipp, PhD
Lead Physiology Modeler
rclipp@ara.com
919-582-3330

Aaron Bray
Lead Software Architect
abray@ara.com
919-582-3333