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A Computer Model of Intracranial Pressure Dynamics during Traumatic Brain Injury that Explicitly Models Fluid Flows and Volumes

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System Science Ph.D. Program

Oregon Health & Science Univ. Complex Systems Laboratory

Objective

- **To create a computer model of intracranial pressure (ICP) dynamics**
- **To use model to evaluate clinical treatment options for elevated ICP during traumatic brain injury (TBI)**
  - ➜ **Present work: replicate response to treatment**
  - ➜ Future Work: predict response to treatment
  - ➜ Long term goal: optimize treatment

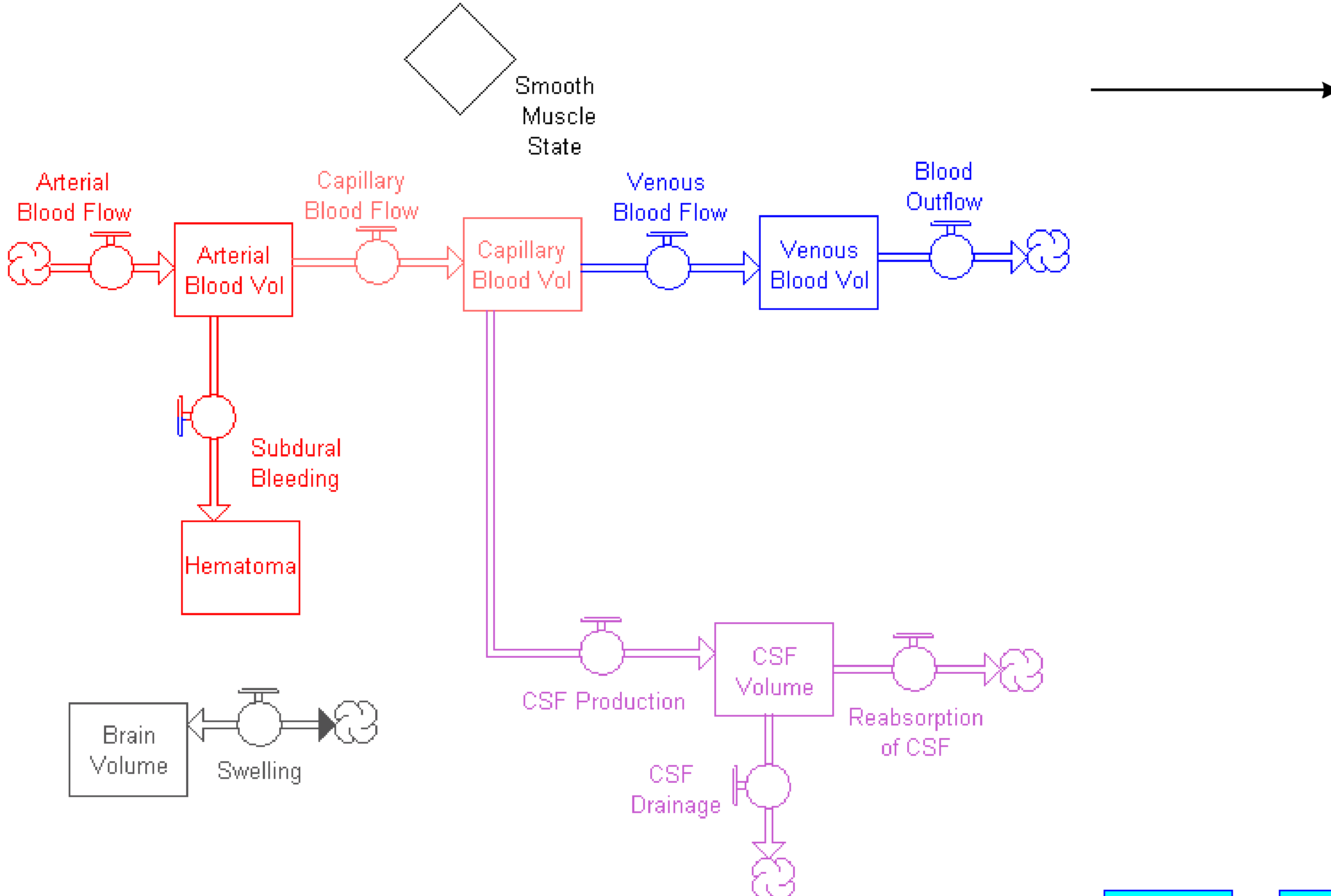
Approach

- Fluid volumes as the primary state variables
  - ➔ Parameters estimated: compliances, resistances, hematoma volume and rate, etc.
  - ➔ Flows and pressures caluculated from state vars. & parameters
  - ➔ Simplified logic used to model cerebrovascular autoregulation
    - ✓ Resistance at arterioles changes rapidly to adjust flow to match metabolic needs, within limits
    - ✓ The logic responds to diurnal variation or changes in ICP, respiration, arterial blood pressure, head of bed (HOB), etc.

Approach (continued)

- Trauma and therapies modeled
  - ➔ Hemorrhage and edema
  - ➔ Cerebrospinal fluid drainage, HOB, respiration rate
- Model calibrated to specific patients based on clinical data
  - ➔ Recorded data includes ICP, ABP, and CVP
  - ➔ Data is clinically annotated
  - ➔ Data is prospectively collected per experimental protocol
    - ✓ Protocol includes CSF drainage, and changes in head of bead and minute ventilation
- Tested capability of model to reproduce correct physiologic response to trauma and therapies

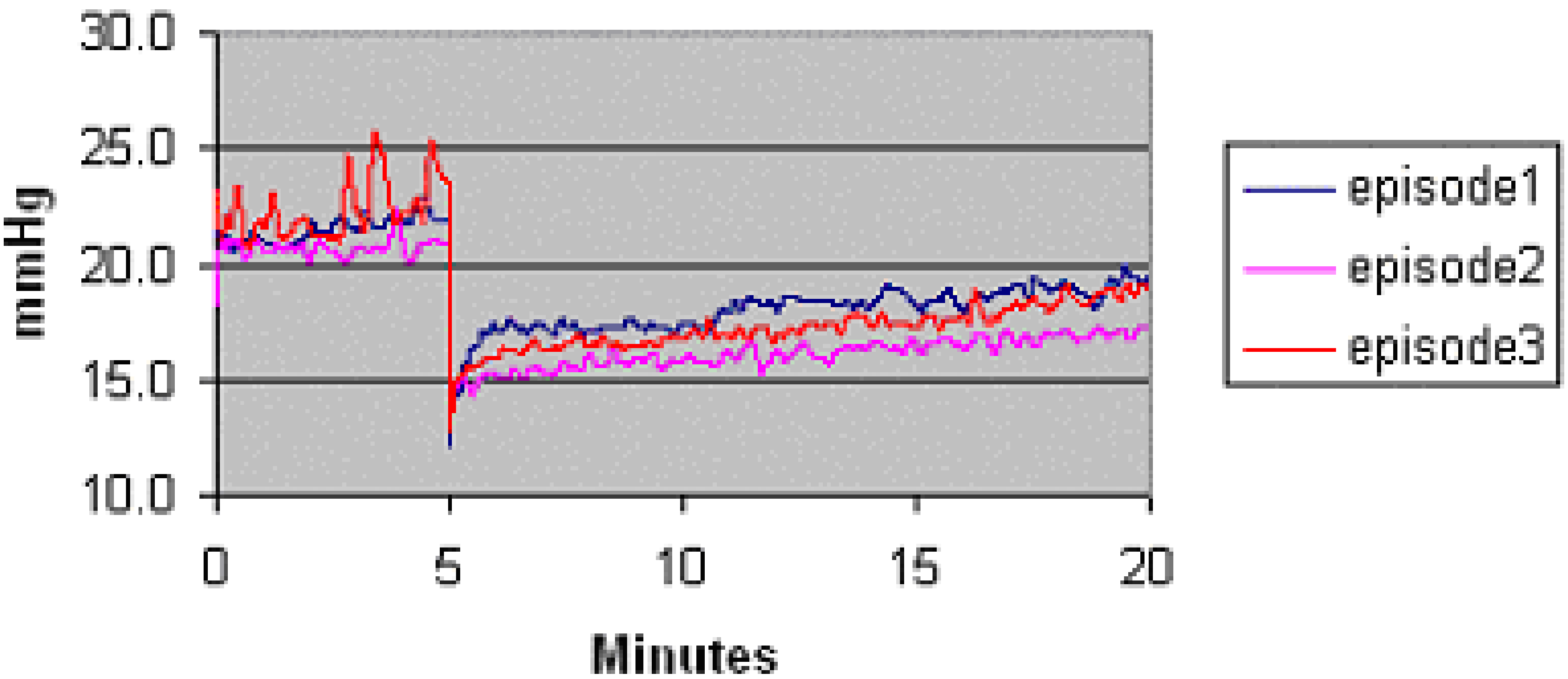
Model State Variables and Flows



Link 2 Full D.

Link to Eqns.

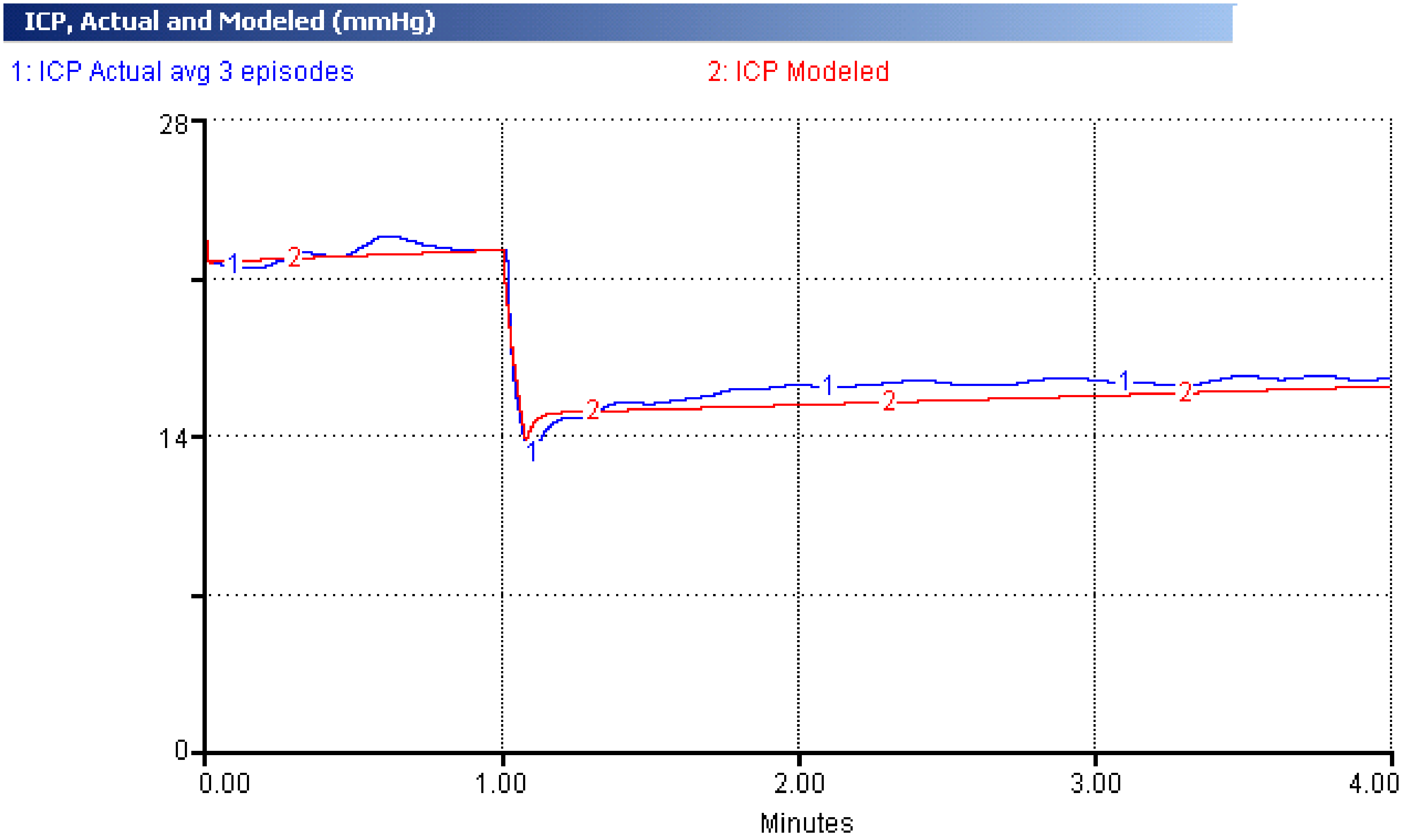
Clinical Data for ICP before and after CSF Drainage, Patient 1



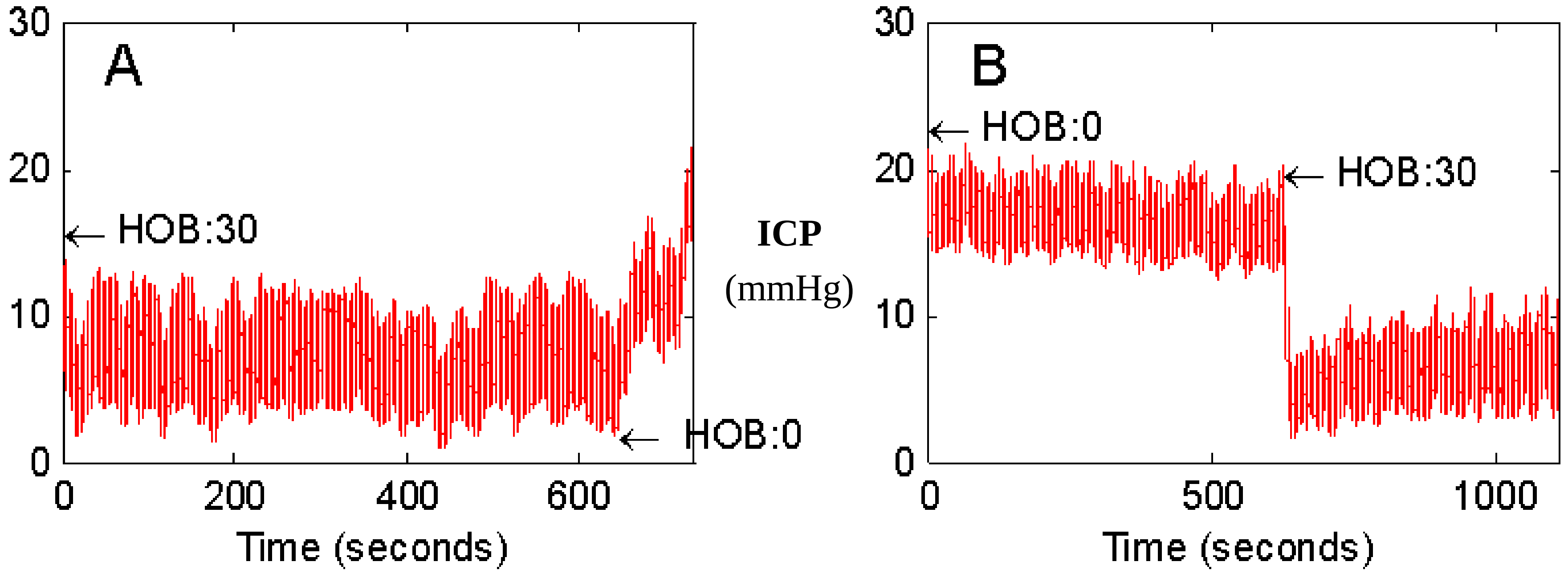
Model Calibrated to Fit the Clinical Data for Patient 1

- Estimated parameters
  - *Initial hematoma volume* = 24 mL
  - *Hematoma increase rate* = 0
  - *CSF drainage volume* = 6.5 mL
  - *CSF uptake resistance* = 160 mmHg/mL/min
    - ✓ This high value implies a significant impediment to flow/uptake
      - → Presumably due either to the initial injury, subsequent swelling, or a combination of the two

Model Response to CSF Drainage, Patient 1



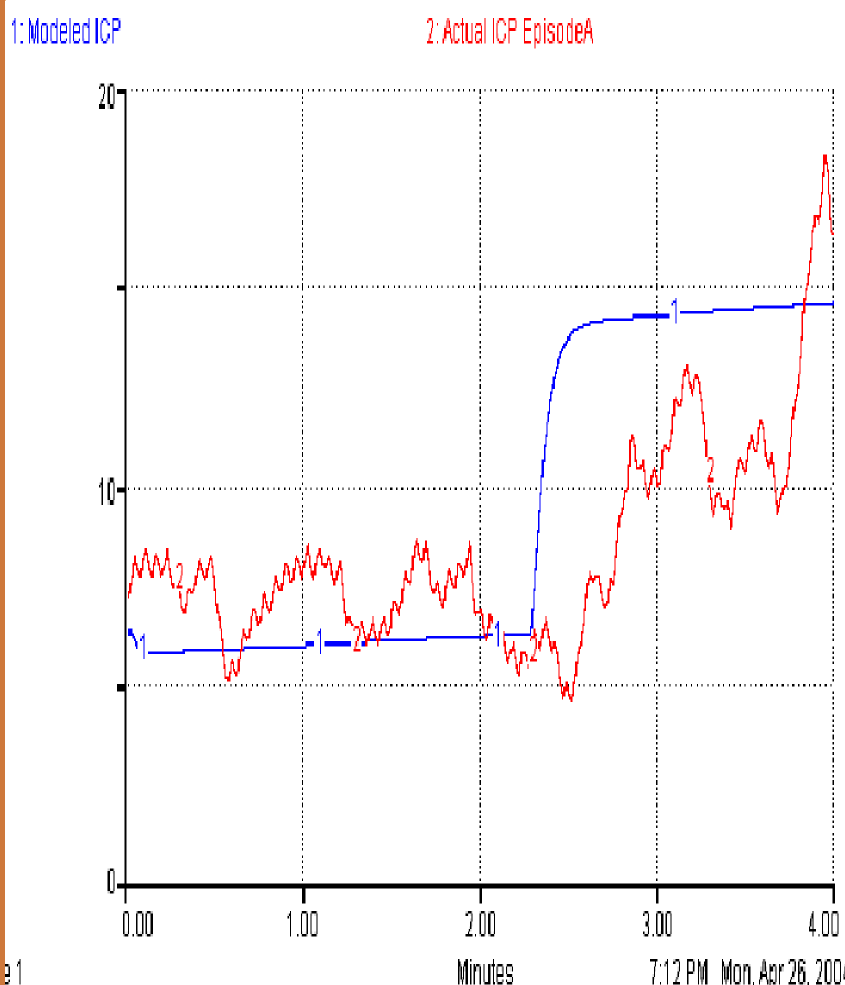
Prospective Clinical Data: Head of Bed Change, Patient 2

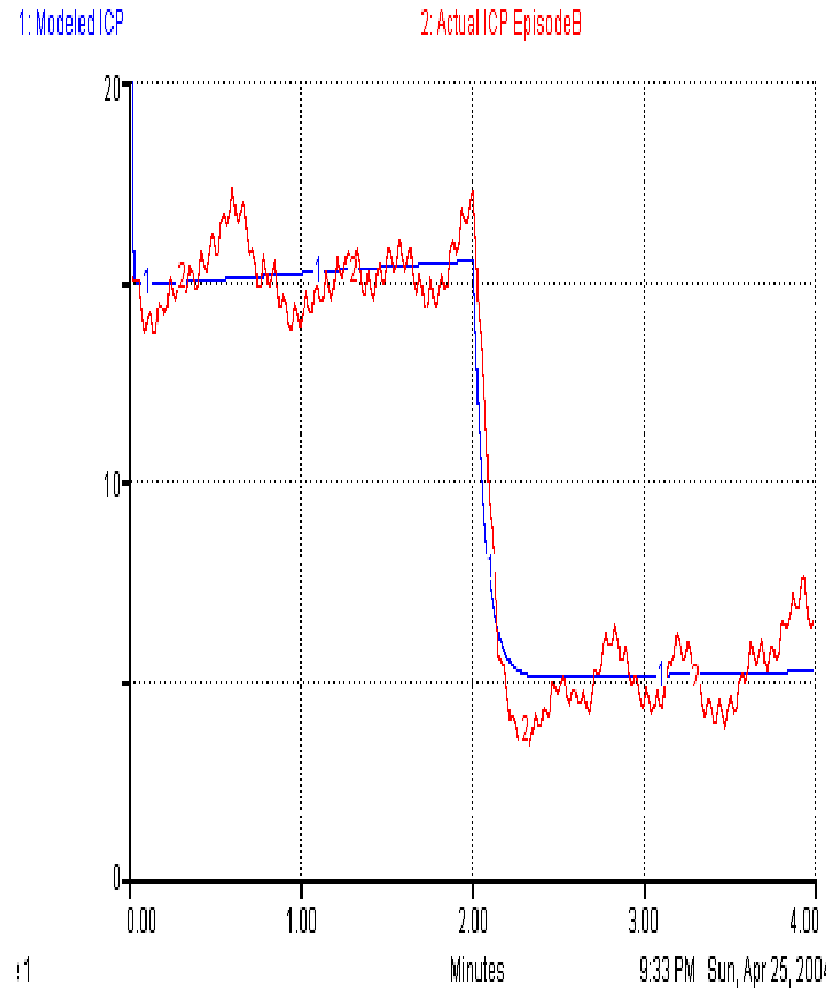


Model Calibration for HOB Change, Patient 2

- Estimated parameters for lowering HOB
  - → *Initial hematoma volume* = 6 mL
  - → *Hematoma increase rate* = .5 mL/min.
  - → *Distance from heart to brain* = 40 cm
  - → *CSF absorption resistance* = 24 mmHg/mL/min
- Estimated parameters for raising HOB
  - → *Hematoma increase rate* = .5 mL/min.
  - → *Distance from heart to brain* = 45 cm (revised est.)

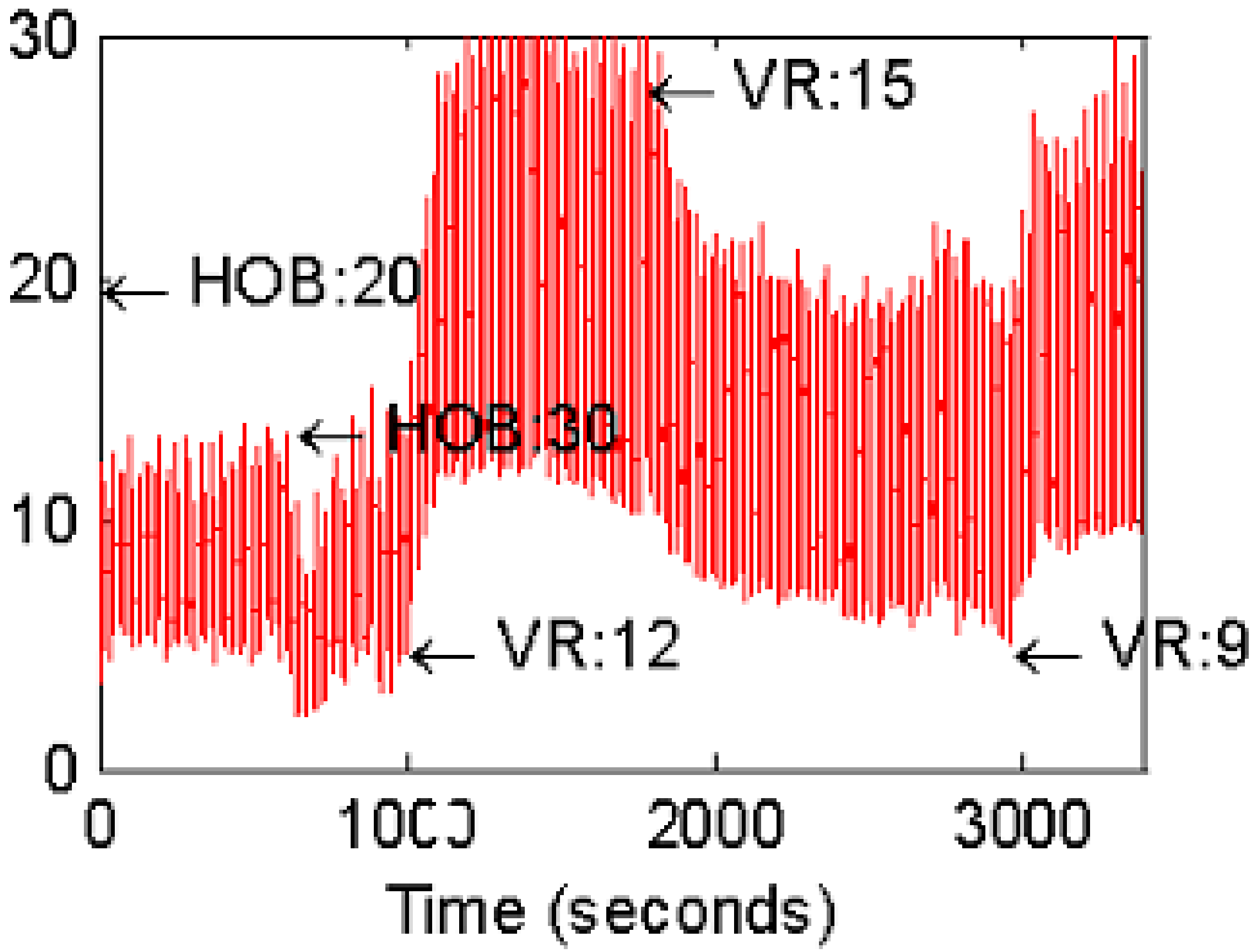
Model Response to Changing HOB, Patient 2





Prospective Clinical Data: Respiration Change, Patient 2

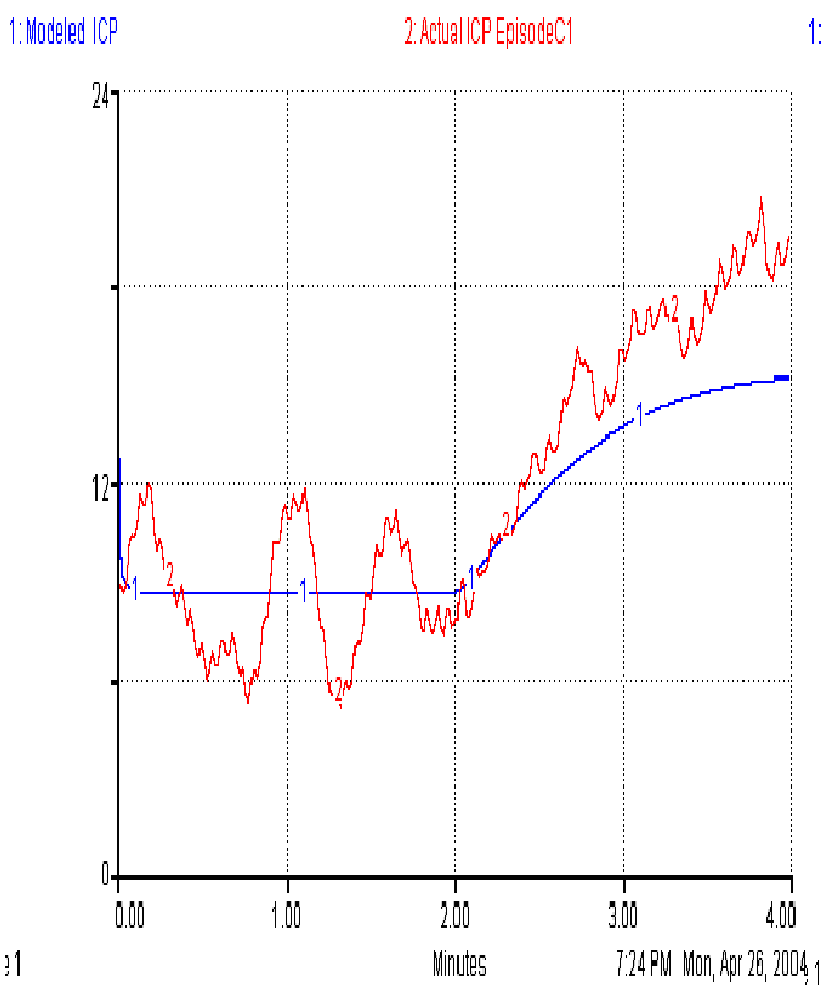
ICP
(mmHg)

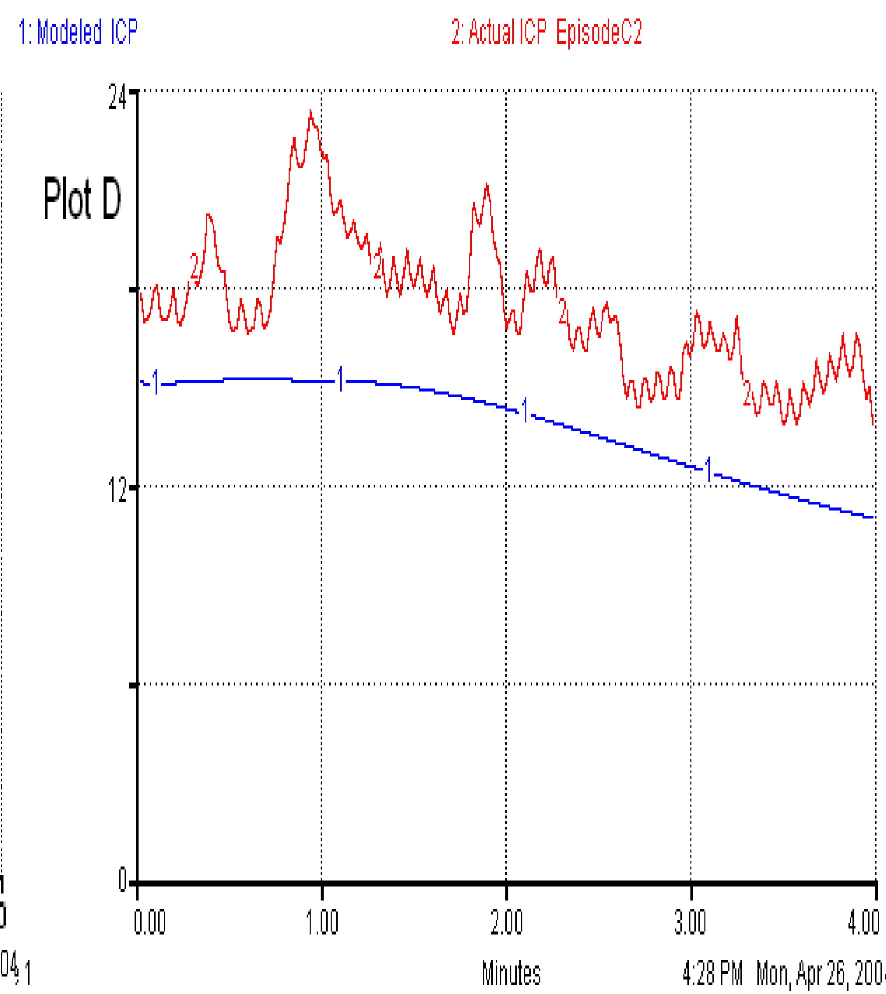


Model Calibration for Respiration Change

- Estimated Parameters for AR process
  - → *Flow multiplier* = 75 ml/mmHg
  - → *$PaCO_2$ setpoint* = 34 mmHg
  - → *$PaCO_2$ offset* = 64 mmHg
  - → *Conversion factor* = 2 mmHg-breaths/min.
  - → *Time constant for $PaCO_2$ response* = 2.5 minutes
- The model was not able to fully replicate patient's response to the VR change
  - → Most likely due to the simplified cerebrovascular autoregulation logic

Model Response to Changing Respiration, Patient 2





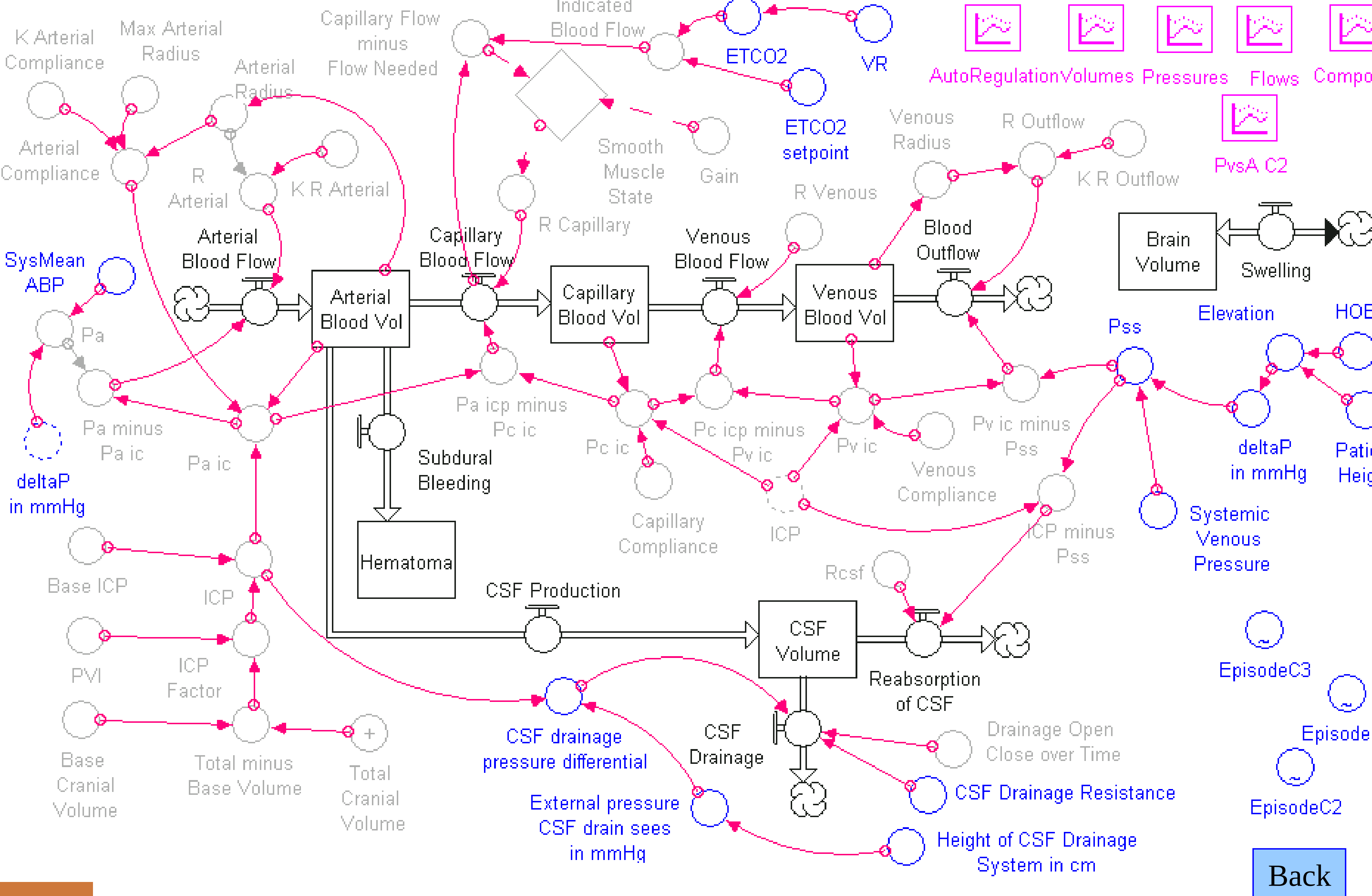
Summary

- We developed a simple model of ICP dynamics that uses fluid volumes as primary state variables
- ICP calculated by the model closely resembles ICP signals recorded during treatment and during an experimental protocol
  - → CSF drainage, changing HOB and respiration
- Cerebrovascular autoregulation logic only partially captured the patient's response to respiration change

Key Variables and Equations

- Six intracranial compartments
  - → Arterial blood (ABV)
  - → Capillary blood (CBV)
  - → Venous blood (VBV)
  - → Cerebral spinal fluid (CSF)
  - → Brain tissue (BTV)
  - → Hematoma (HV)
- Compartmental pressures
  - → P_{ab} = ICP + (ABV)/(Arterial Compliance)
  - → P_{cb} = ICP + (CBV)/(Capillary Compliance)
  - → P_{vb} = ICP + (VBV)/(Venous Compliance)
- Intracranial Pressure (ICP)
  - → $\text{ICP} = \text{BaseICP} \times 10^{(\text{Total Cranial Volume} - \text{Base Cranial Volume})/\text{PVI}}$

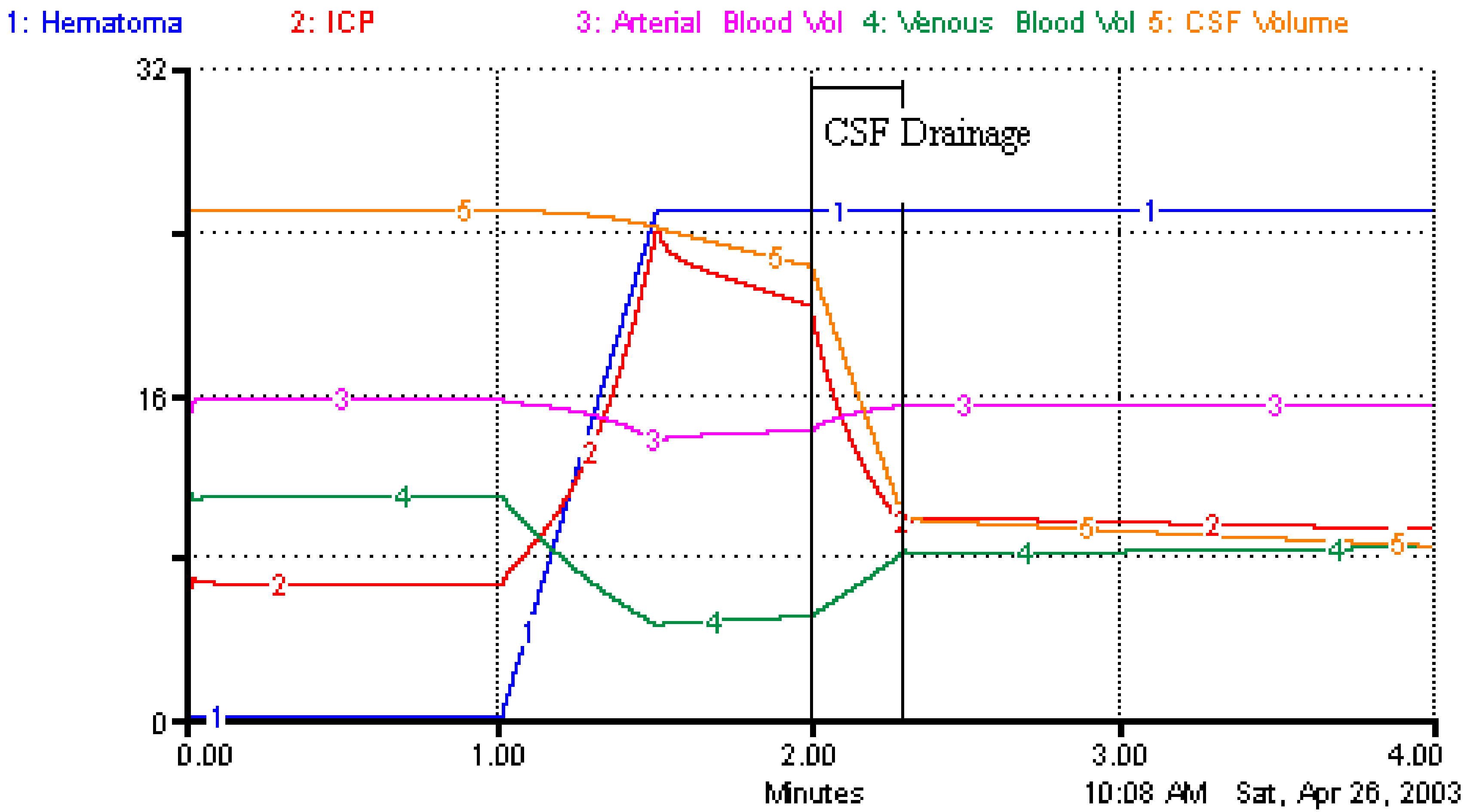
Back


K Arterial Compliance
Max Arterial Radius
Arterial Radius
Capillary Flow minus Flow Needed
Indicated Blood Flow
ETCO2
VR
ETCO2 setpoint
AutoRegulation
Volumes
Pressures
Flows
Compos
PvsA C2
Arterial Compliance
R Arterial
K R Arterial
Smooth Muscle State
Gain
Venous Radius
R Outflow
K R Outflow
R Venous
R Capillary
Arterial Blood Flow
Capillary Blood Flow
Venous Blood Flow
Blood Outflow
Brain Volume
Swelling
SysMean ABP
Arterial Blood Vol
Capillary Blood Vol
Venous Blood Vol
Elevation
HOB
Pss
Pa
Pa icp minus Pc ic
Pc icp minus Pv ic
Pv ic minus Pss
Pa minus Pa ic
Pa ic
Pc ic
Pv ic
Venous Compliance
deltaP in mmHg
Patien Heigh
deltaP in mmHg
Subdural Bleeding
Capillary Compliance
ICP
ICP minus Pss
Systemic Venous Pressure
Hematoma
Base ICP
ICP
CSF Production
Rcsf
CSF Volume
EpisodeC3
PVI
ICP Factor
Reabsorption of CSF
EpisodeC
CSF Drainage
Drainage Open Close over Time
Base Cranial Volume
Total minus Base Volume
Total Cranial Volume
CSF drainage pressure differential
External pressure CSF drain sees in mmHg
CSF Drainage Resistance
EpisodeC2
Height of CSF Drainage System in cm
Back

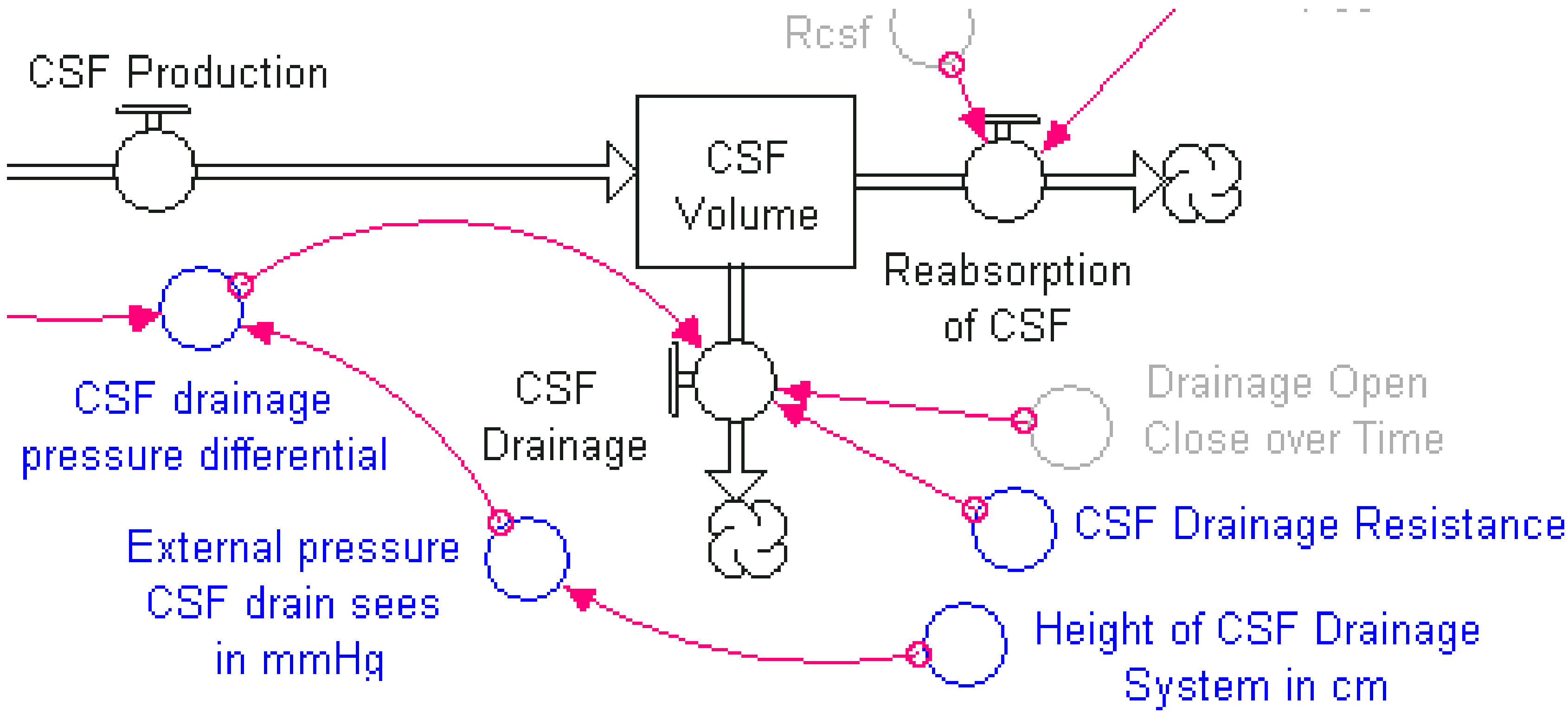
Hypothetical Test of the Model

	1.0-1.5 min.	2.0-2.3 min.
Perturba-tion	•Arterial blood escapes to form a 25 mL hematoma	•12 mL Cerebral spinal fluid drained
Response	•ICP increases to 24 mmHg •Venous and arterial blood is forced from the cranial vault	•ICP decreases to 10 mmHg •Venous and arterial blood volumes normalize

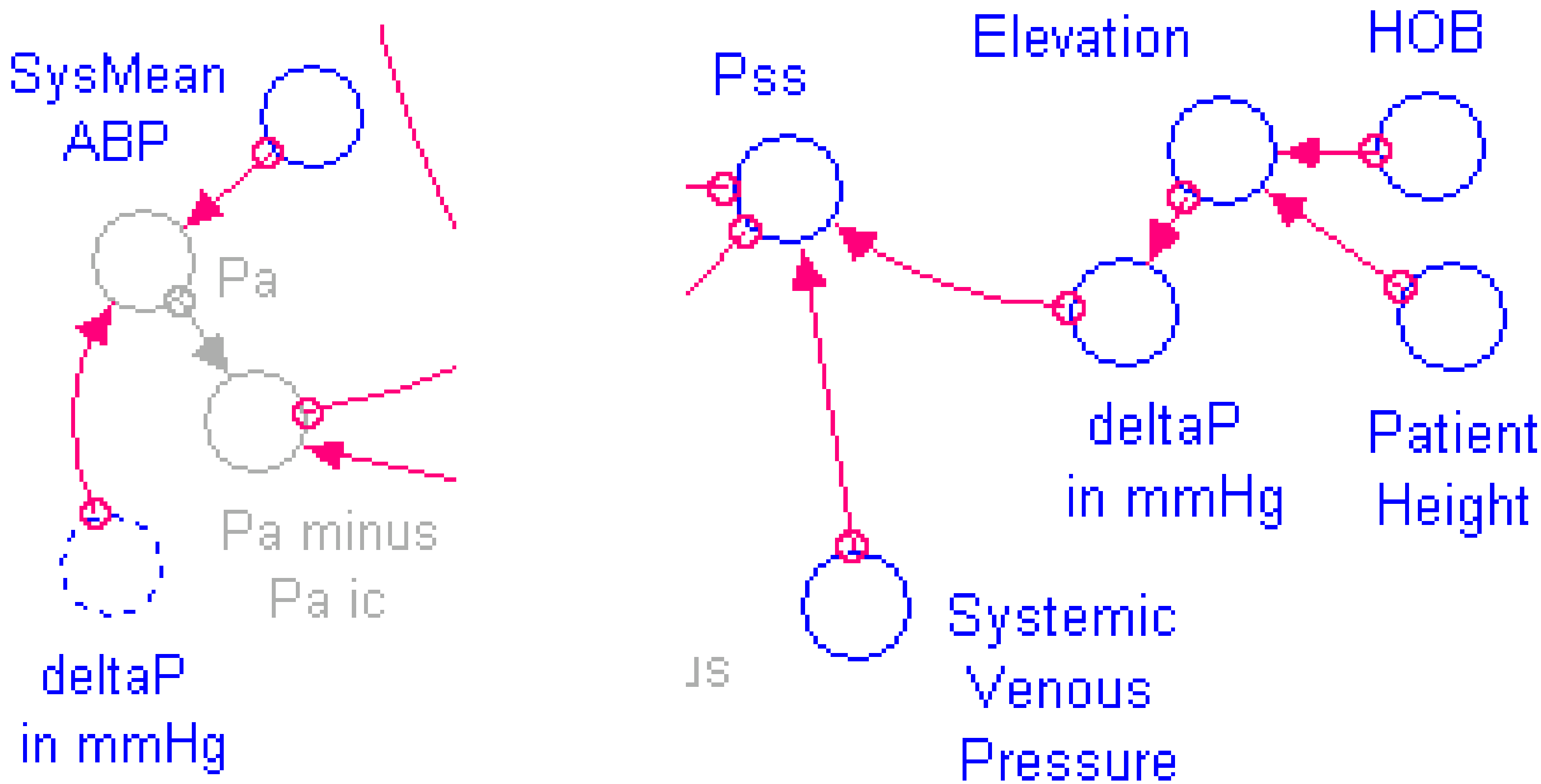
Time Plot for Hypothetical Test of Model



CSF Drainage Submodel



Head of Bed Logic



Cerebrovascular Autoregulation (AR) Logic

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