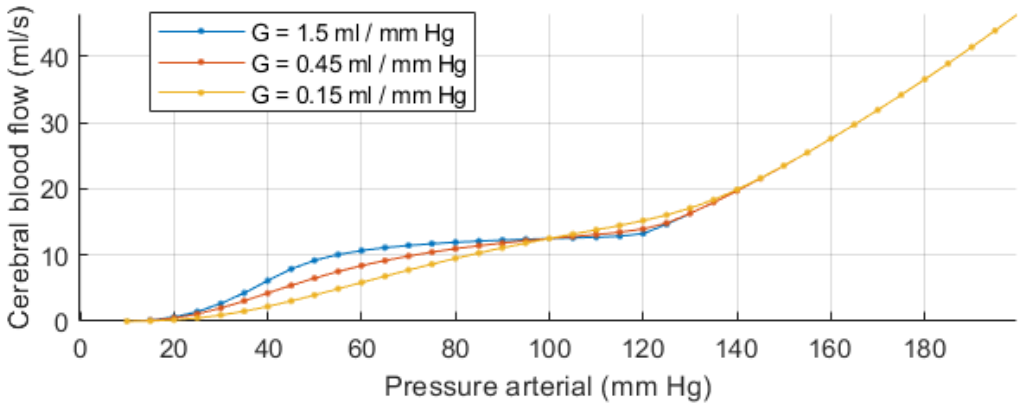
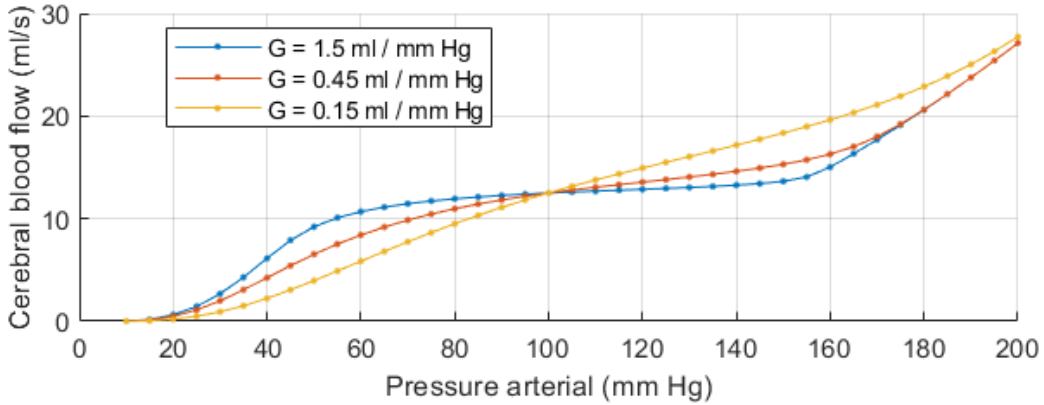
Kompleksowy model dynamiki wewnątrzczaszkowego ciśnienia płynu mózgowo-rdzeniowego: modyfikacja modelu elektrycznego Ursino przy użyciu oprogramowania Matlab/Simulink

Leszek Herbowski , Oddział Neurochirurgii, Szczecin


G = 1.5 ml / mm Hg
G = 0.45 ml / mm Hg
G = 0.15 ml / mm Hg
Cerebral blood flow (ml/s)
Pressure arterial (mm Hg)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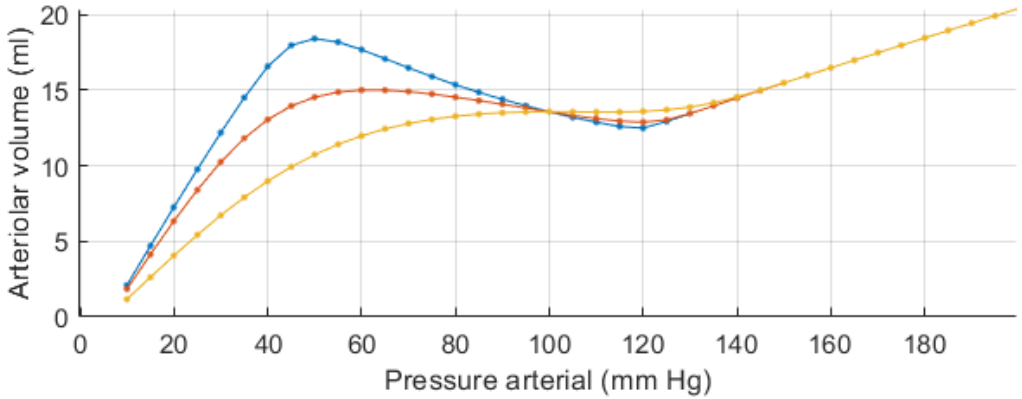
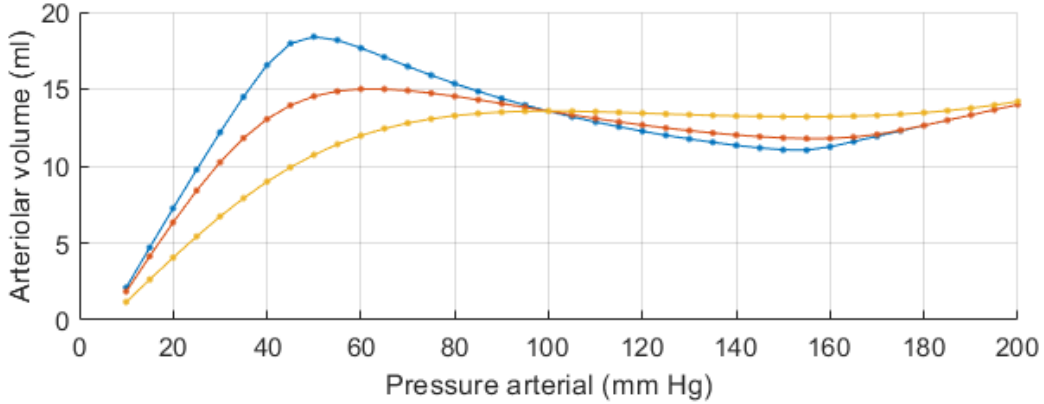
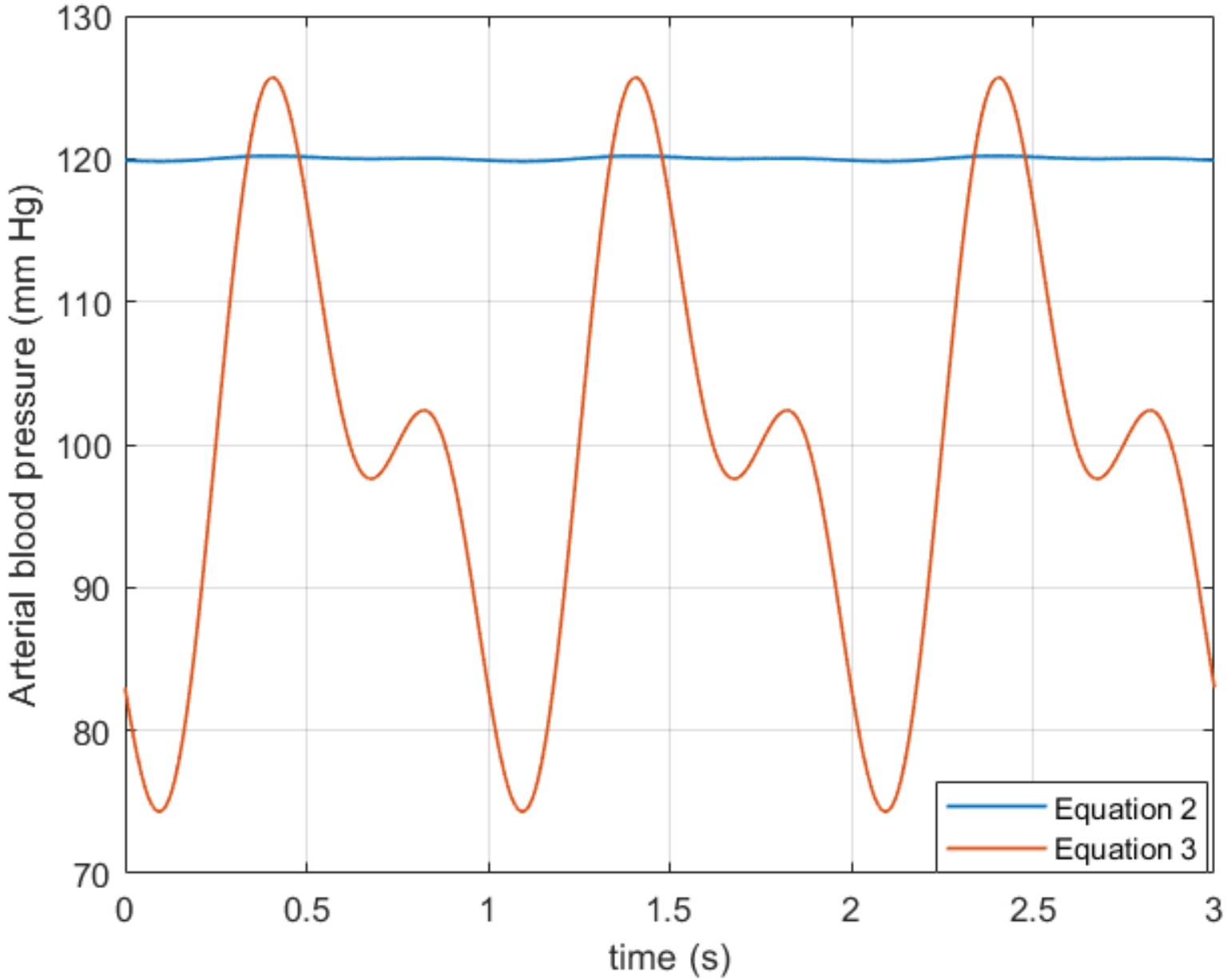
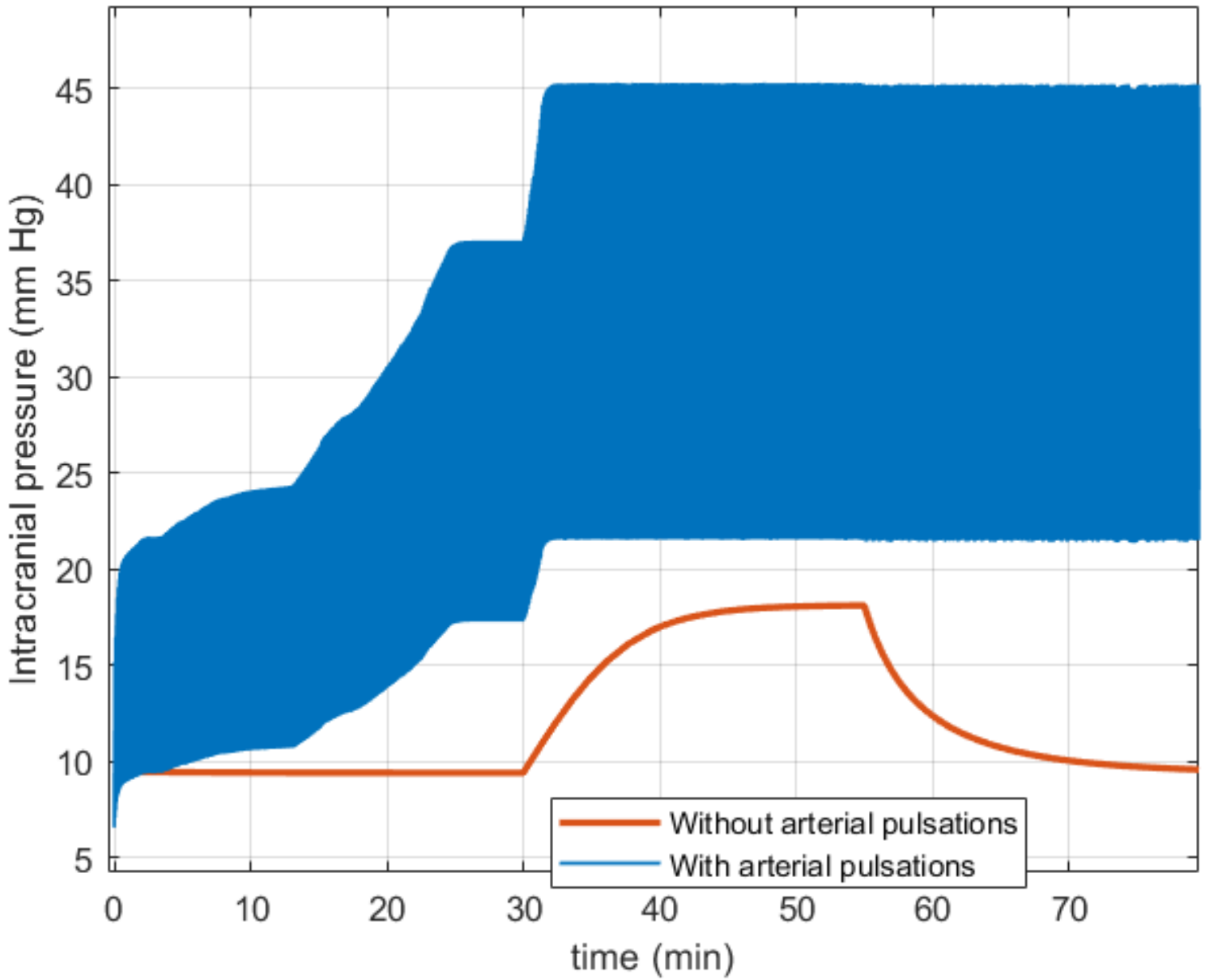
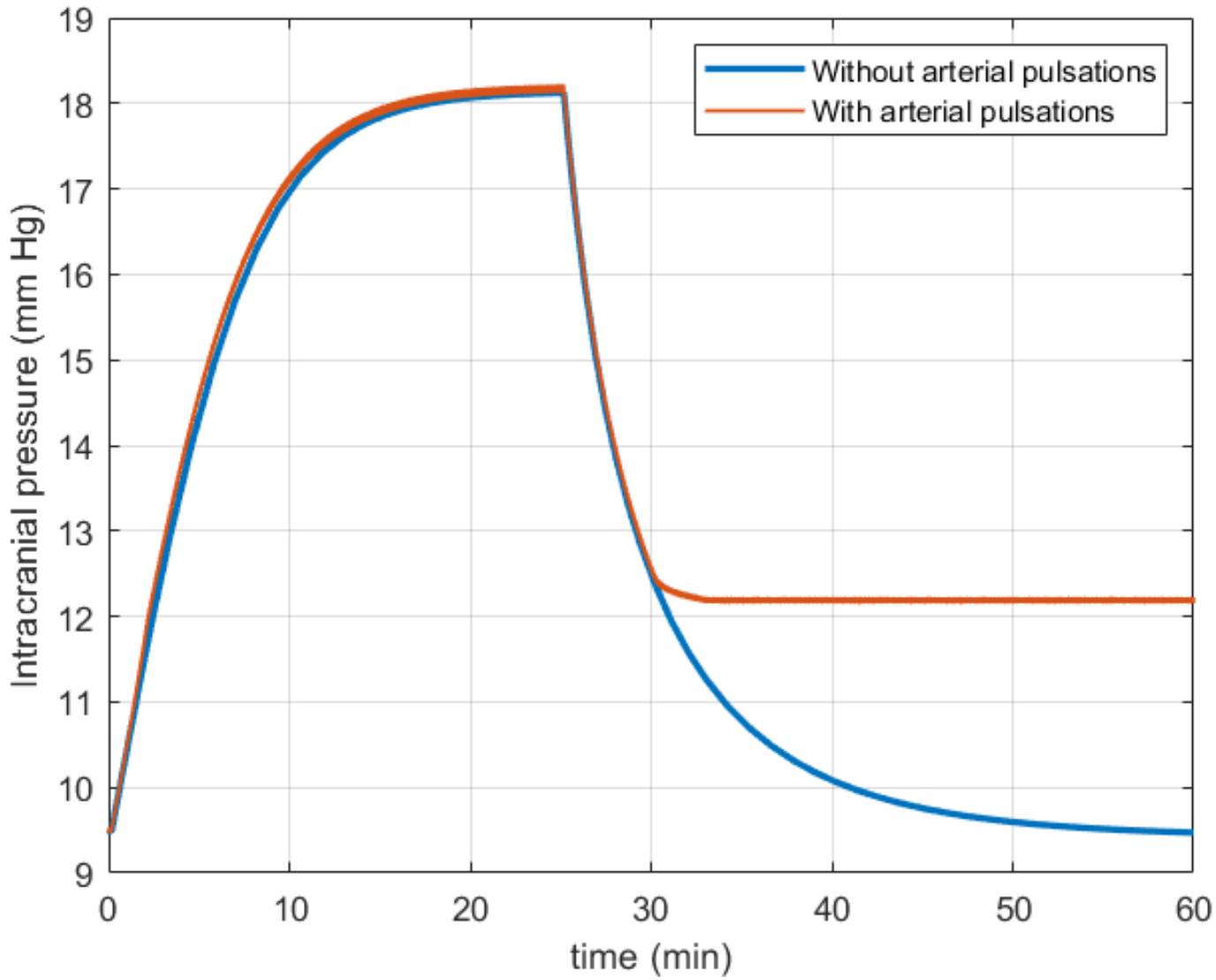

Arteriolar volume (ml)
Pressure arterial (mm Hg)


Arteriolar volume (ml)
Pressure arterial (mm Hg)


130
120
110
100
90
80
70
Arterial blood pressure (mm Hg)
0
0.5
1
1.5
2
2.5
3
time (s)
Equation 2
Equation 3

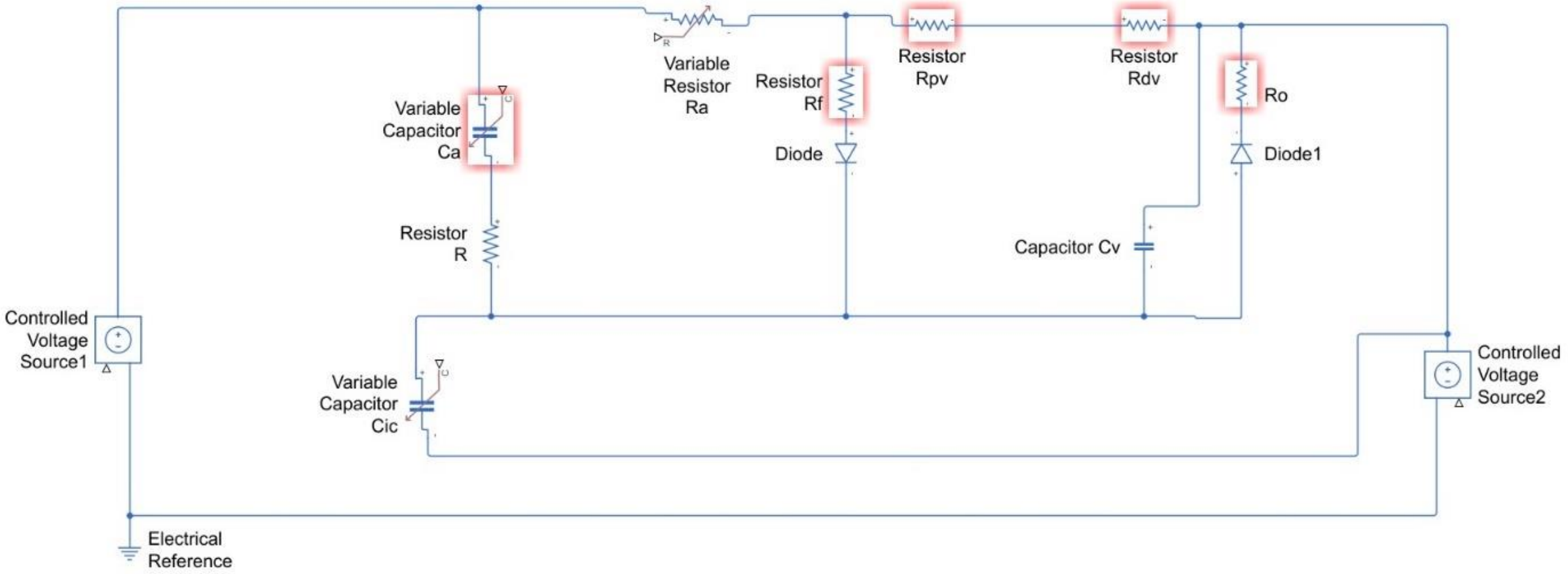

Intracranial pressure (mm Hg)
45
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
time (min)
Without arterial pulsations
With arterial pulsations

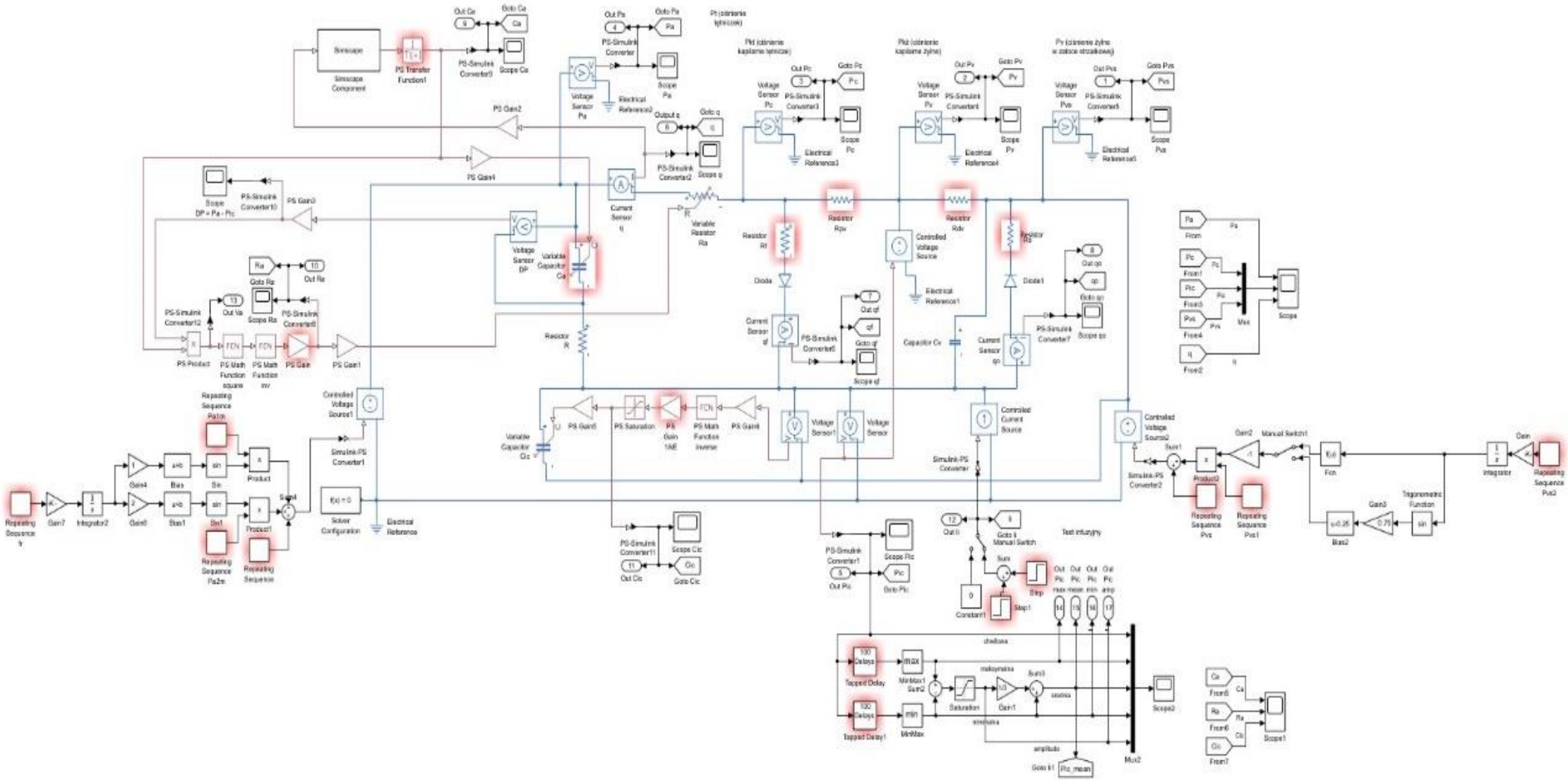

Without arterial pulsations
With arterial pulsations
Intracranial pressure (mm Hg)
time (min)
19
18
17
16
15
14
13
12
11
10
9
0
10
20
30
40
50
60

*A new electrical component ** Modified in my own version

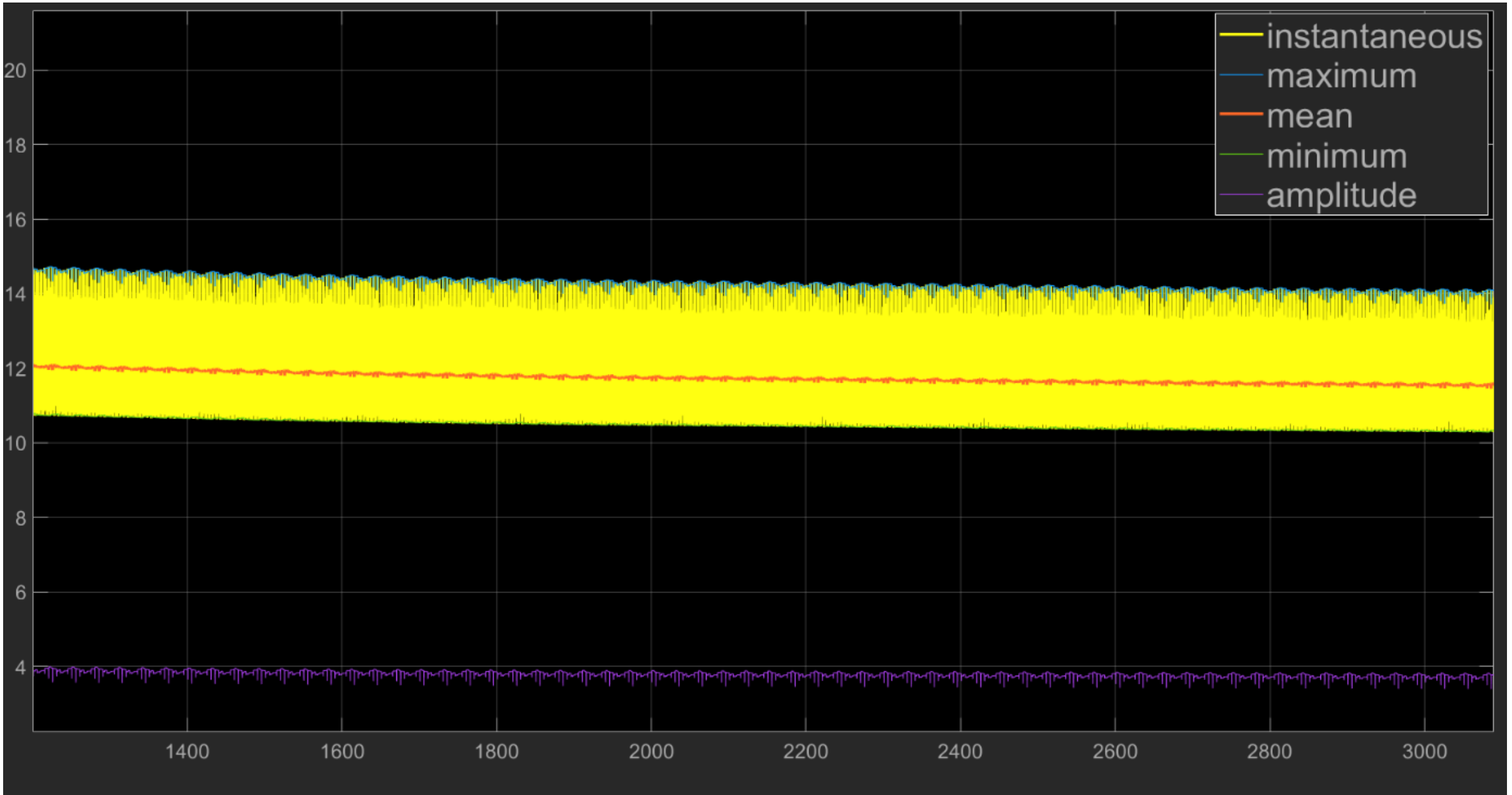
Parameter	Value	Note
R_o (cerebrospinal fluid outflow resistance)	Input signal	526.3 mmHg/(ml/s) by Ursino
R_{pv} (proximal venous resistance)	1.24 mmHg/(ml/s)	
R_f (cerebrospinal fluid formation resistance)	2.38×10^3 mmHg/(ml/s)	
R (additional resistance)	2.0 mmHg/(ml/s)	*
ΔC_{a1} (maximal amplitude of sigmoidal curve)	1.50 ml/mmHg	
ΔC_{a2} (minimal amplitude of sigmoidal curve)	2x0.075 ml/mmHg	**
C_{an} (basal arterial compliance)	0.15 ml/mmHg	
k_E (elastance coefficient)	0.11 ml^{-1}	
k_R (resistance coefficient)	4.91×10^4 mmHg/ml	
τ (time constant for autoregulation)	20 s	
q_n (normal cerebral blood flow)	12.5 ml/s	
G (central autoregulation gain)	1.5 ml/mmHg·100% CBF $change^{-1}$	
P_a (systemic arterial pressure)	Input signal	100 mmHg by Ursino
ICP (intracranial pressure)	Output signal	9.5 mmHg by Ursino
P_c (capillary ressure)	25 mmHg	
P_{vs} (dural sinus pressure)	Input signal	**
C_a (arterial compliance)	0.15 ml/mm Hg	
Capacitor Cv (venous compliance)	0.01 F	**

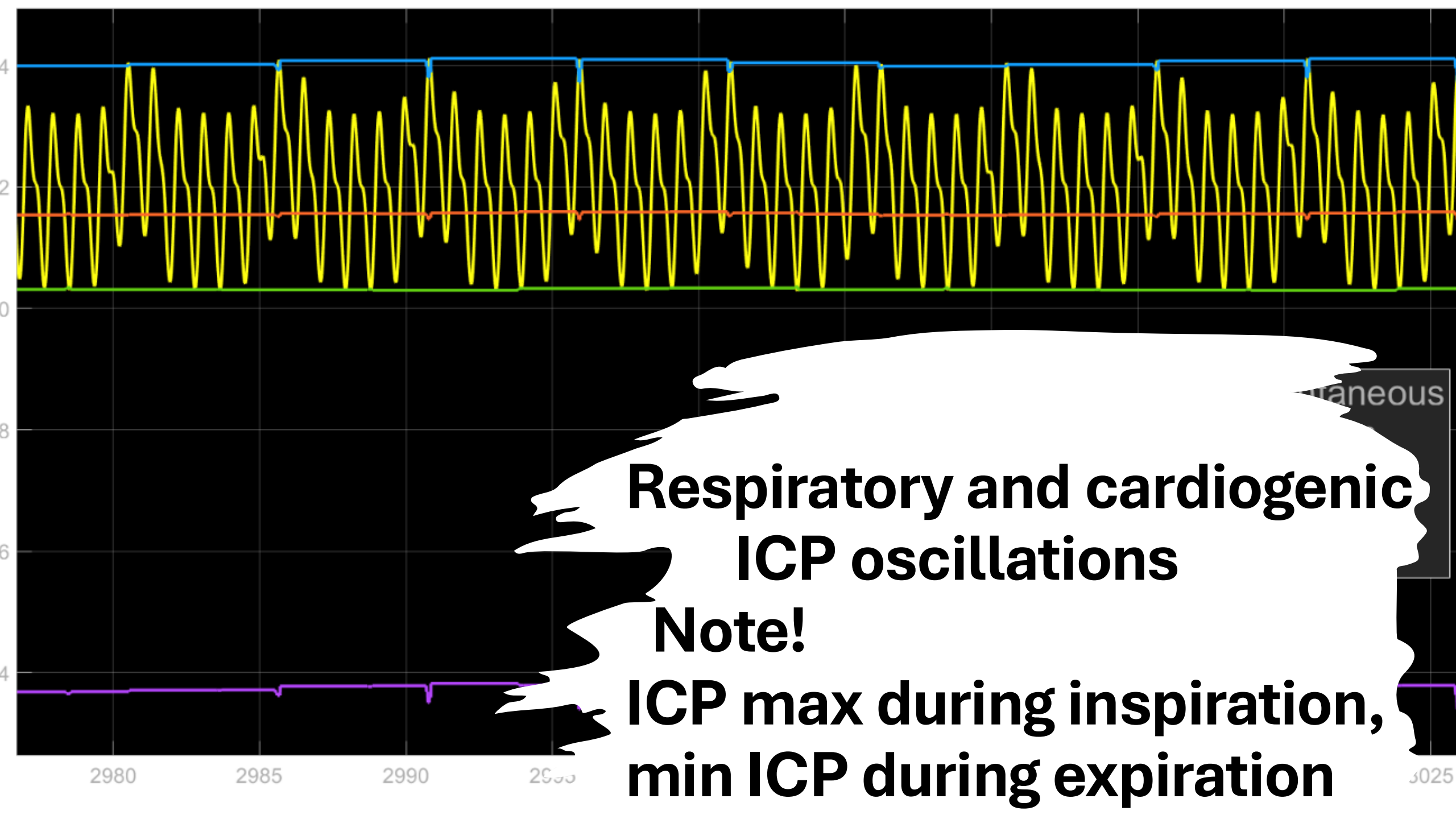
Hybrid electrical-numerical-simulation model

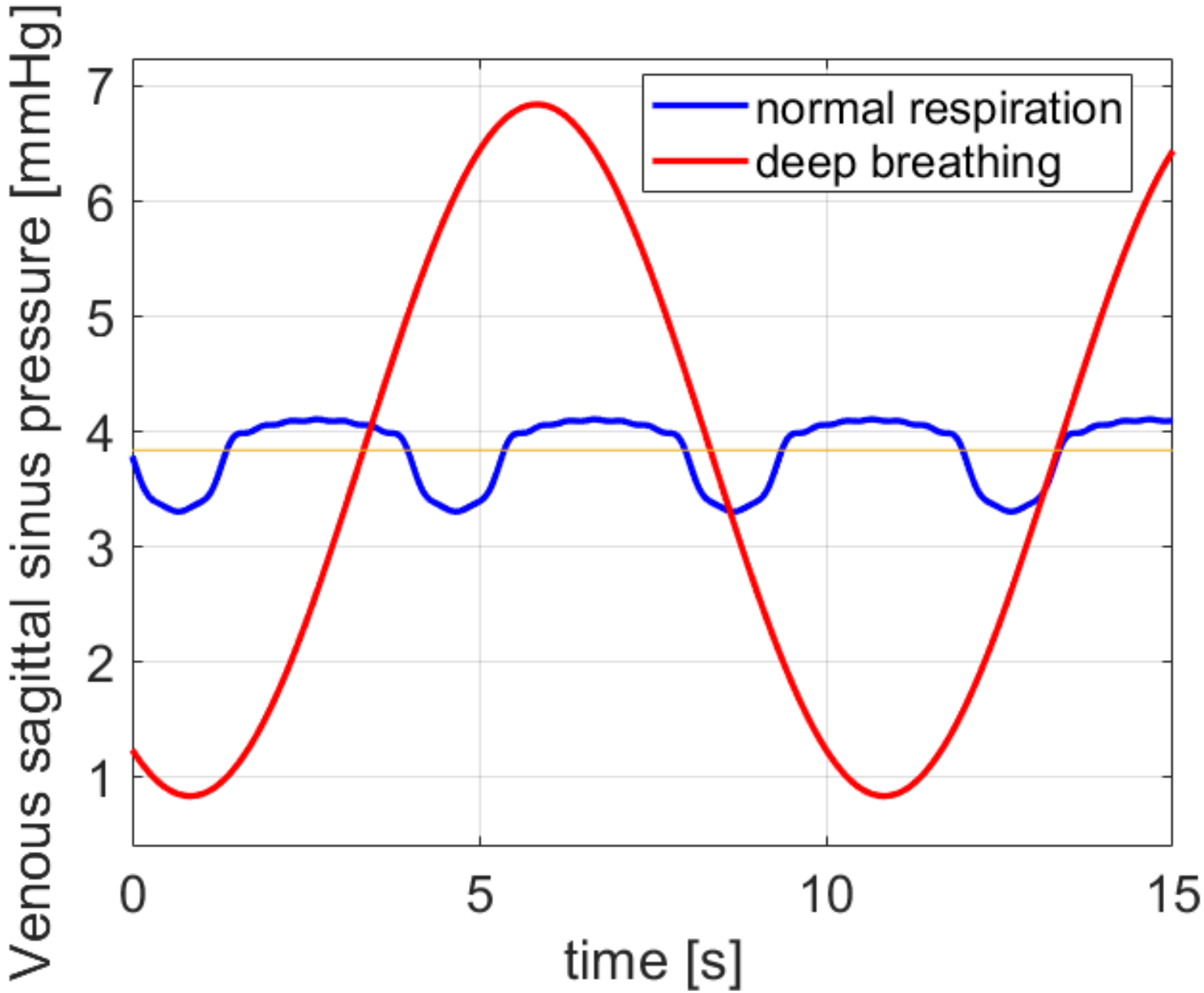


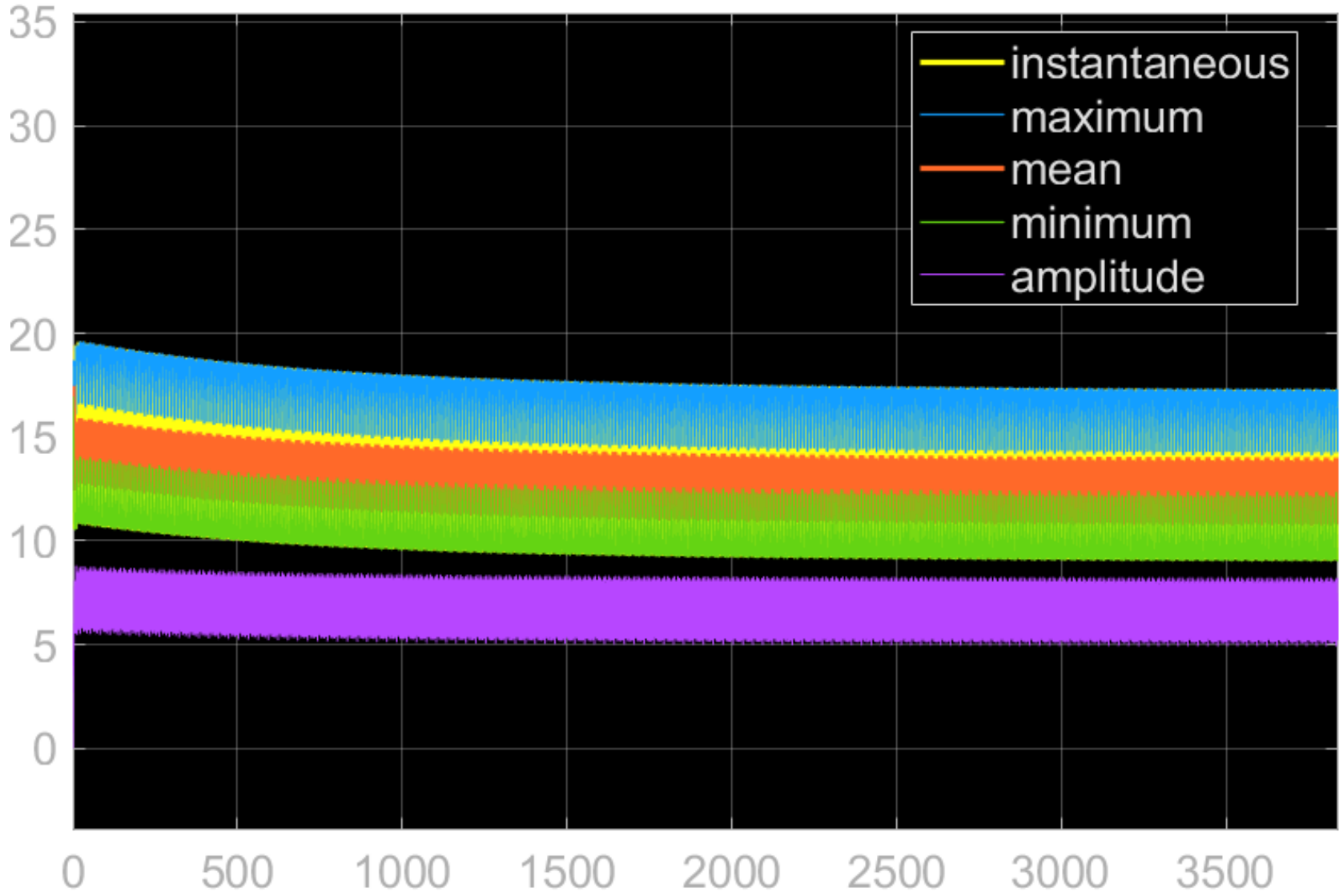

Simscape
Simscape Component
PS Transfer Function1
PS-Simulink Converter3
Scope Ca
Out Ca
Goto Ca
Out Ps
Goto Pa
PS-Simulink Converter
Scope Pa
Voltage Sensor Pa
Electrical Reference2
Pt (ciśnienie tętniczek)
Pkt (ciśnienie kapilarne tętnicze)
Pkt (ciśnienie kapilarne żylne)
Pv (ciśnienie żylne w zatoce strzałkowej)
Voltage Sensor Pc
PS-Simulink Converter3
Scope Pc
Electrical Reference3
Voltage Sensor Pv
PS-Simulink Converter4
Scope Pv
Electrical Reference4
Voltage Sensor Pvs
PS-Simulink Converter5
Scope Pvs
Electrical Reference5
PS Gain2
PS Gain4
PS-Simulink Converter2
Scope q
Output q
Goto q
Current Sensor q
Variable Resistor Ra
Resistor Rpv
Resistor Rdv
Resistor Rf
Resistor Rs
Controlled Voltage Source
Electrical Reference1
Diode
Diode1
Current Sensor qf
PS-Simulink Converter6
Scope qf
Out qf
Goto qf
Capacitor Cv
Current Sensor qo
PS-Simulink Converter7
Scope qo
Out qo
Goto qo
Scope
Scope DP = Pa - Pic
PS-Simulink Converter10
PS Gain3
Voltage Sensor DP
Variable Capacitor Ca
Resistor R
Goto Ra
Out Ra
Scope Ra
PS-Simulink Converter12
Out Va
PS-Simulink Converter8
PS Product
PS Math Function square
PS Math Function inv
PS Gain
PS Gain1
Controlled Voltage Source1
Simulink-PS Converter1
Repeating Sequence Pa1m
Repeating Sequence Pa2m
Repeating Sequence
Gain7
Integrator2
Gain4
Gain6
Bias
Bias1
Sin
Sin1
Product
Product1
Sum4
Solver Configuration
Electrical Reference
Variable Capacitor Cic
PS Gain5
PS Saturation
PS Gain 1AE
PS Math Function inverse
PS Gain4
Voltage Sensor1
Voltage Sensor
Controlled Current Source
Simulink-PS Converter
Controlled Voltage Source2
Simulink-PS Converter2
Sum1
Product2
Repeating Sequence Pvs
Repeating Sequence Pvs1
Gain2
Manual Switch1
Fcn
Integrator
Gain
Repeating Sequence Pvs2
Gain3
Bias2
Trigonometric Function
PS-Simulink Converter11
Scope Cic
Out Cic
Goto Cic
PS-Simulink Converter1
Scope Pic
Out Pic
Goto Pic
Out Ii
Goto Ii
Manual Switch
Test intuzyjny
Sum
Step
Constant1
Step1
Out Pic max
Out Pic mean
Out Pic min
Out Pic amp
chwilowa
Tapped Delay
Tapped Delay1
MinMax1
Sum2
Saturation
Gain1
Sum3
maksymalna
minimalna
amplitudo
Goto Ii1
Pic_mean
Mux2
Scope2
Scope1
From
From1
From3
From4
From2
From5
From6
From7
Mux

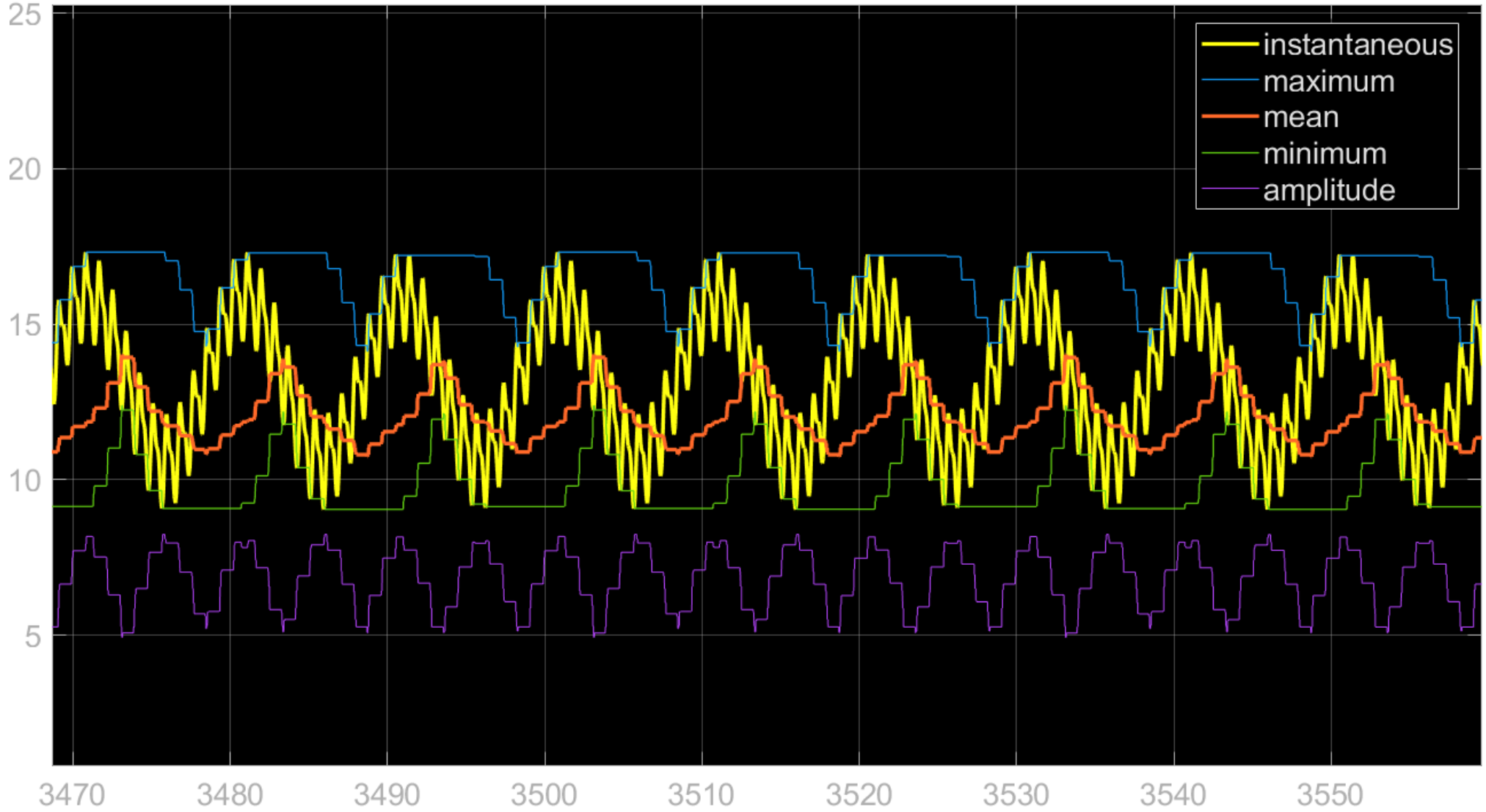
Free ICP recording

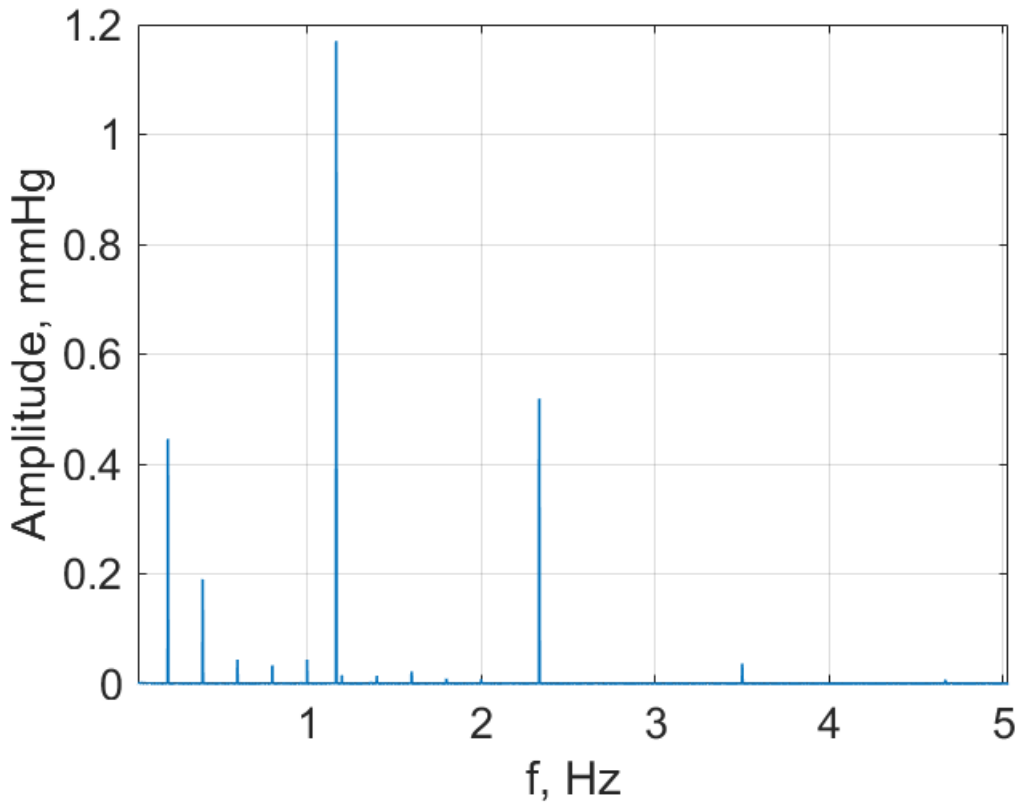


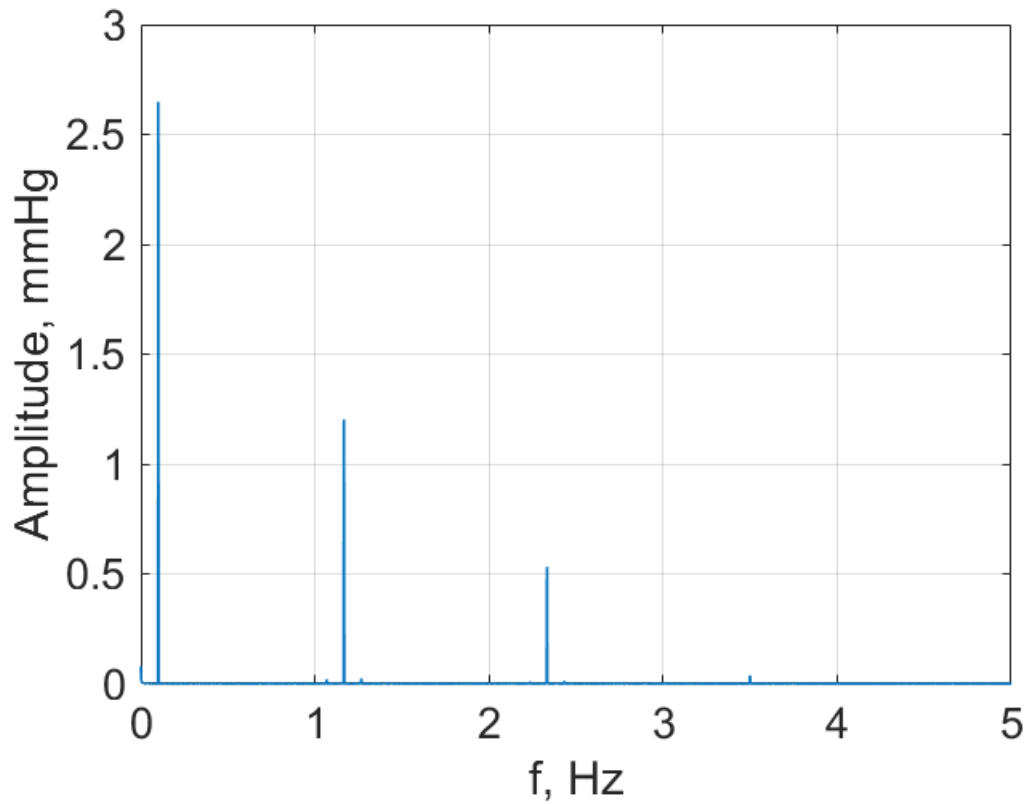

Respiratory and cardiogenic
ICP oscillations
Note!
ICP max during inspiration,
min ICP during expiration
2980
2985
2990


Venous sagittal sinus pressure [mmHg]
7
6
5
4
3
2
1
0
5
10
15
time [s]
normal respiration
deep breathing

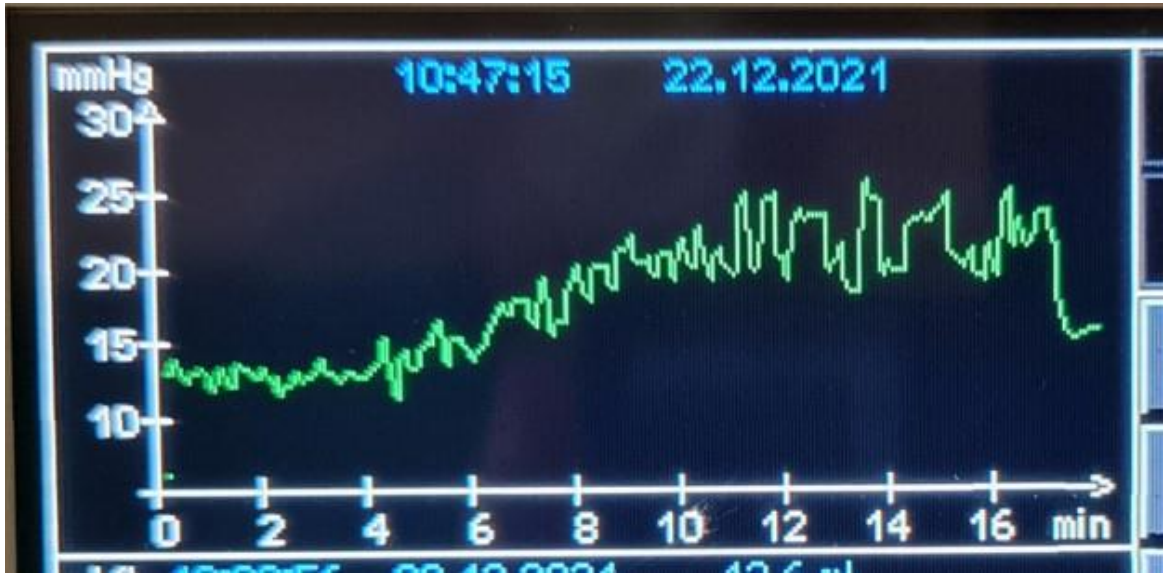

35
30
25
20
15
10
5
0
0
500
1000
1500
2000
2500
3000
3500
instantaneous
maximum
mean
minimum
amplitude

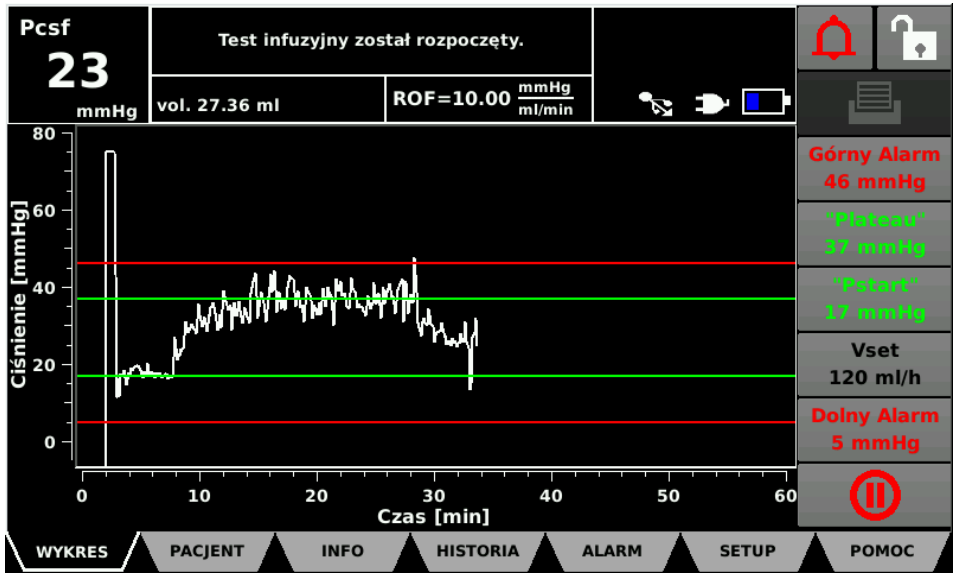

25
20
15
10
5
3470
3480
3490
3500
3510
3520
3530
3540
3550
instantaneous
maximum
mean
minimum
amplitude


1.2
1
0.8
0.6
0.4
0.2
0
Amplitude, mmHg
1
2
3
4
5
f, Hz


3
2.5
2
1.5
1
0.5
0
Amplitude, mmHg
0
1
2
3
4
5
f, Hz

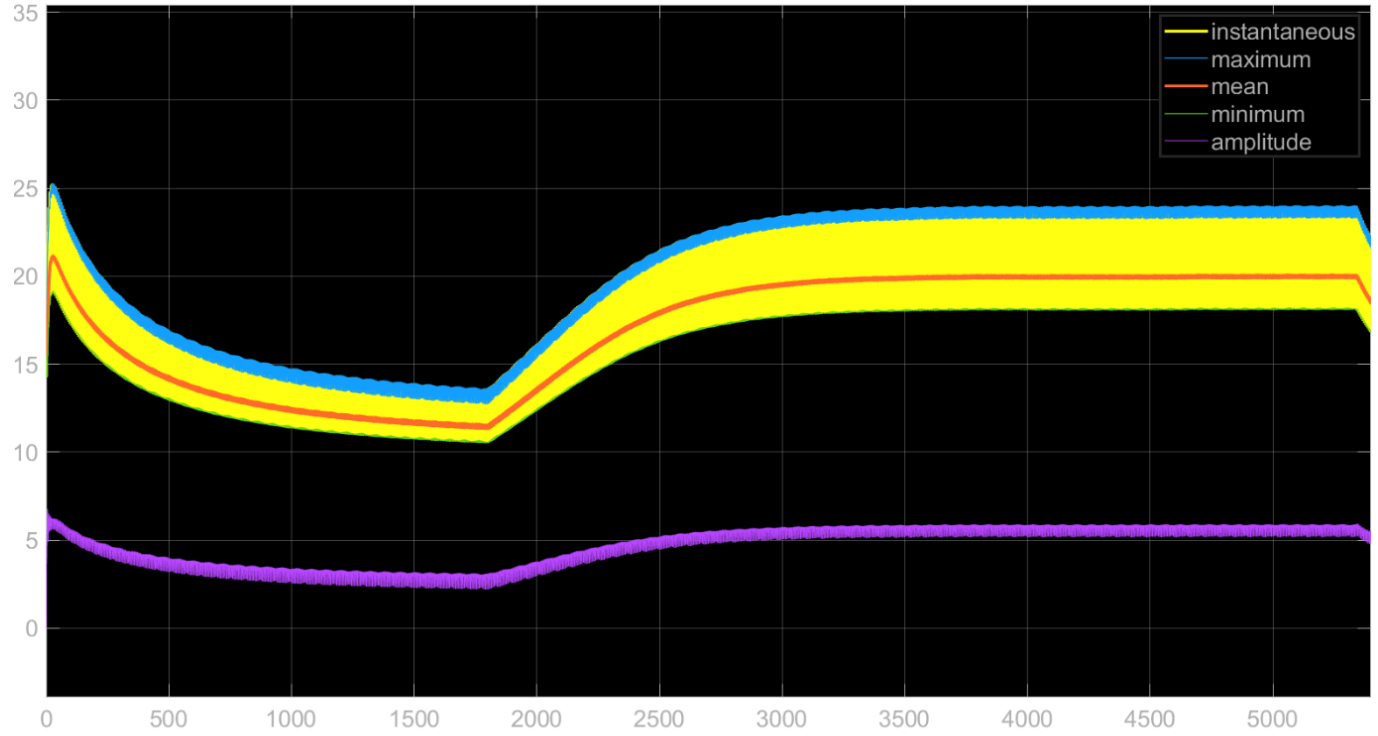
Test Infuzyjny u 21 chorych z podejrzeniem wodogłowia normotensyjnego



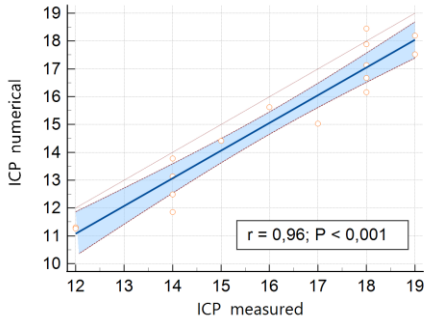


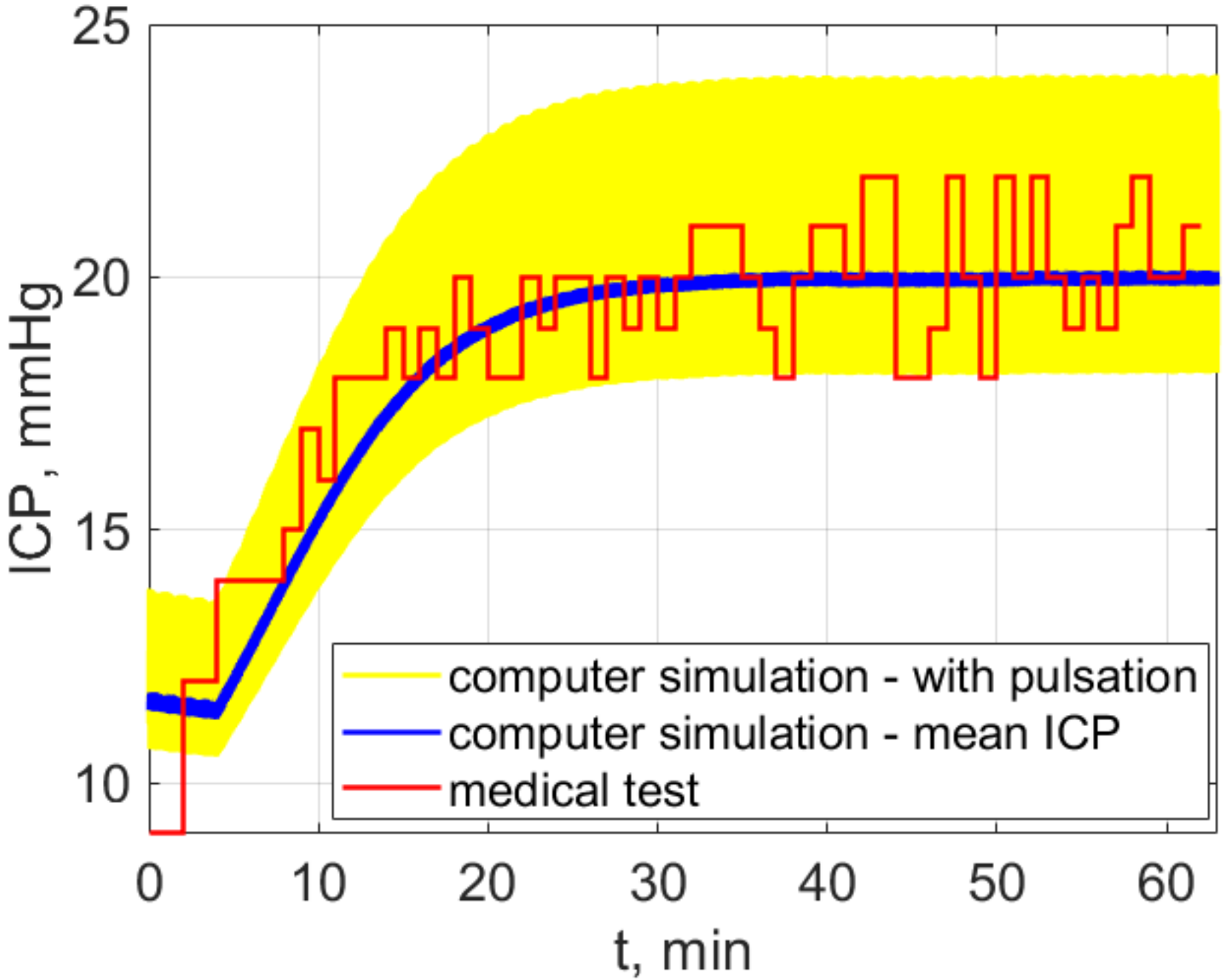
SYMULACJA testu infuzyjnego

Infusion test

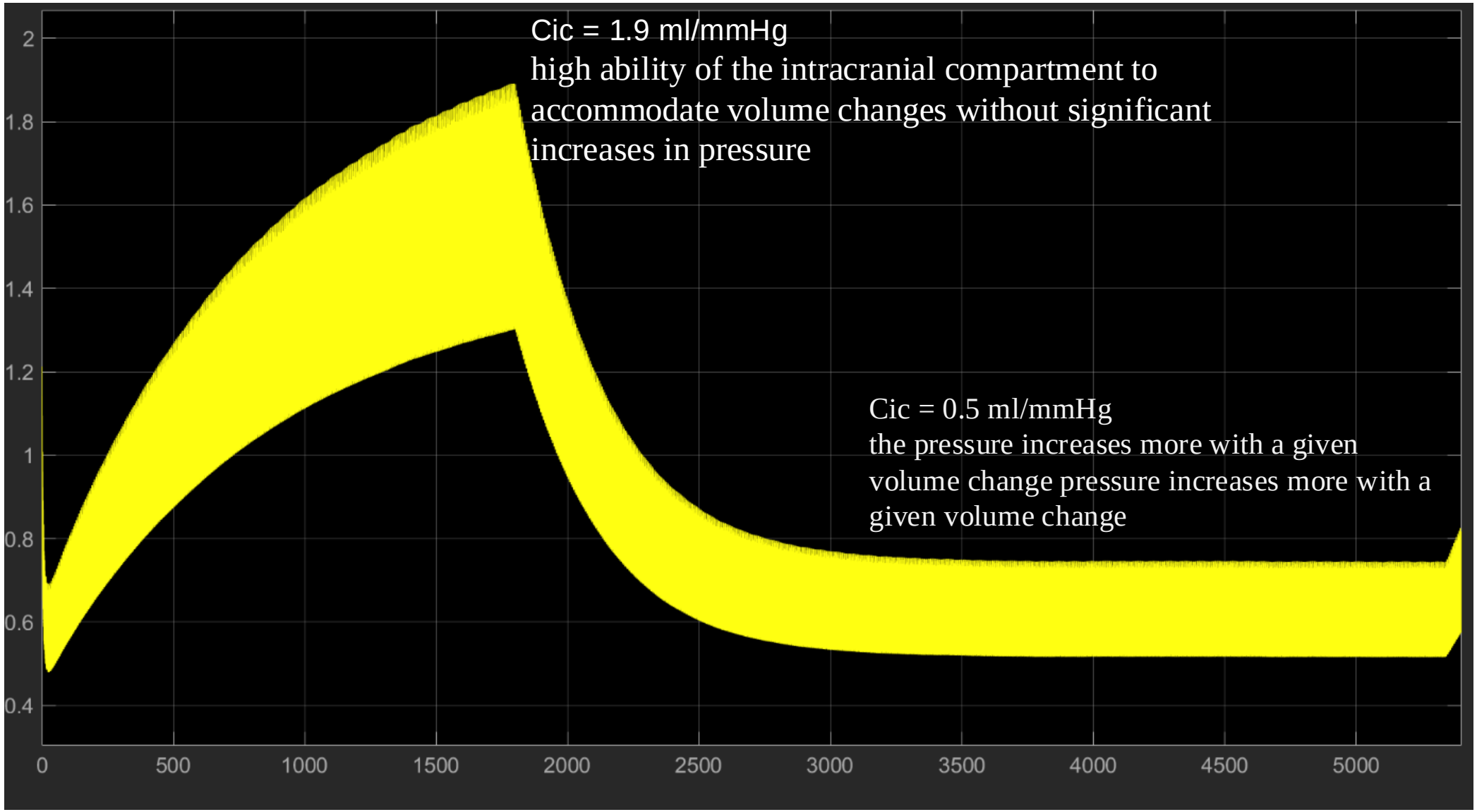


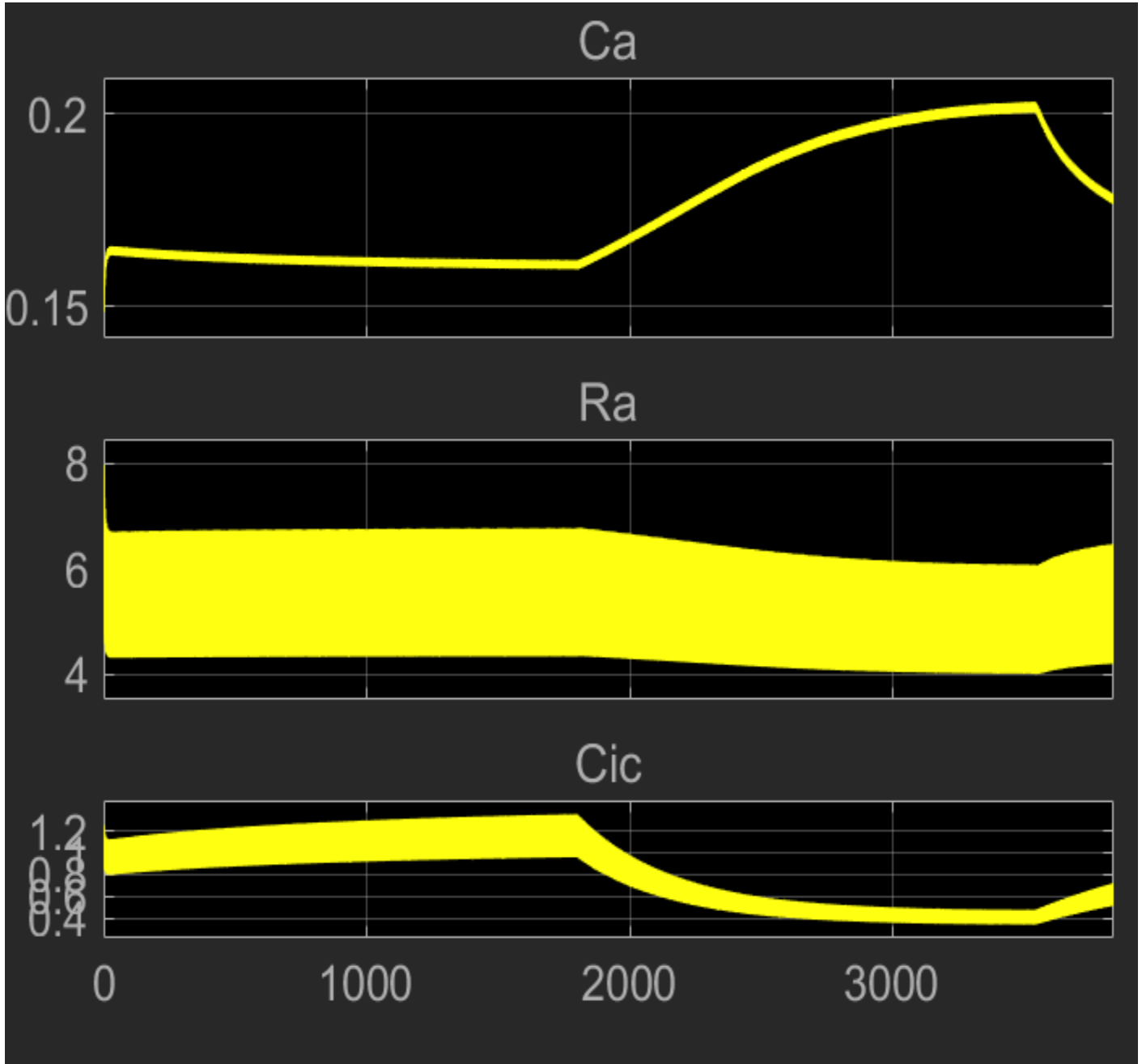
R = 0.96




25
20
15
10
ICP, mmHg
0
10
20
30
40
50
60
t, min
computer simulation - with pulsation
computer simulation - mean ICP
medical test

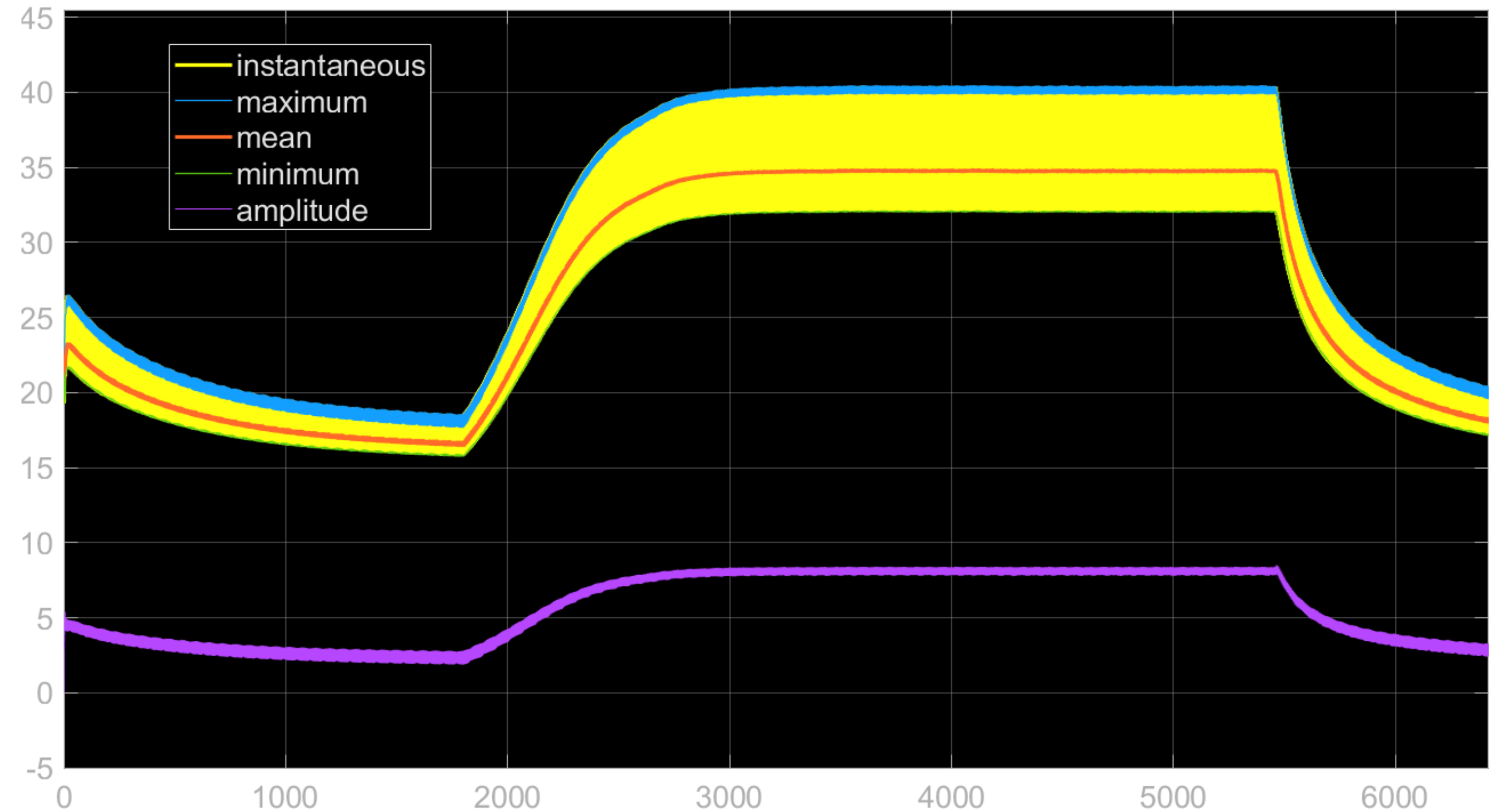
Intracranial Compliance





Output signals

- Ca (arterial Compliance)
- Ra (arterial Resistance)
-Cic (intracranial Compliance)


instantaneous
maximum
mean
minimum
amplitude
45
40
35
30
25
20
15
10
5
0
-5
0
1000
2000
3000
4000
5000
6000

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Conclusion/Discussion

- W porównaniu do istniejących modeli dynamiki ciśnienia wewnątrzczaszkowego (ICP), zmodyfikowany model analogowy układu elektrycznego wykazuje wyższą dokładność predykcyjną i wierność fizjologiczną, ze średnim współczynnikiem korelacji wynoszącym 0,95 (R2 = 0,9)

- Ten poziom precyzji przewyższa wcześniej zgłaszane modele, które zwykle wykazują współczynniki korelacji w zakresie od 0,7 do 0,9

- Zwiększona wydajność tego modelu może być przypisana zaawansowanym technikom kalibracji dostosowanym do pacjenta

- Wyniki te pokazują potencjał modelu jako wartościowego narzędzia do zastosowań klinicznych (ICP, Compliance) oraz badawczych.