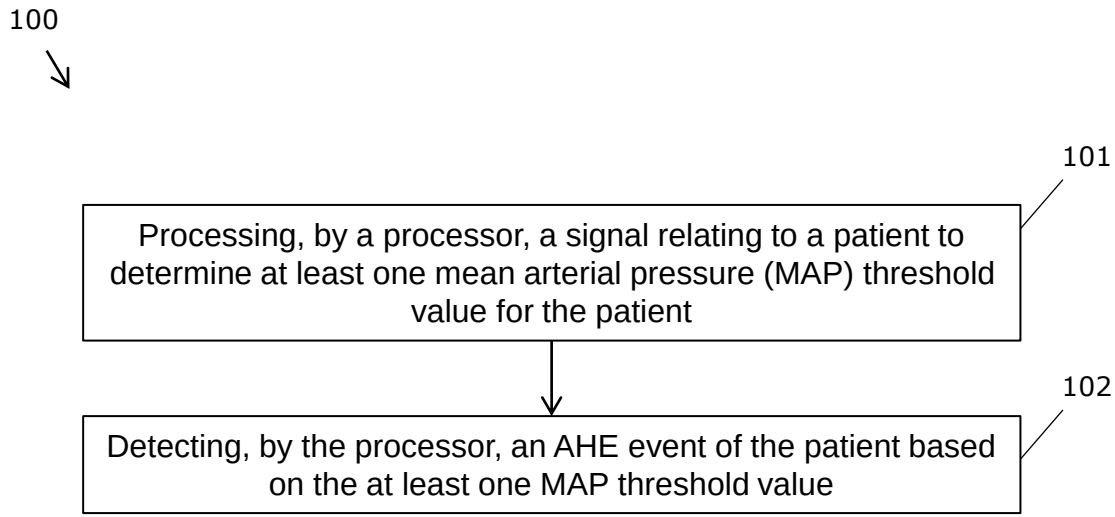

100
101
Processing, by a processor, a signal relating to a patient to determine at least one mean arterial pressure (MAP) threshold value for the patient
102
Detecting, by the processor, an AHE event of the patient based on the at least one MAP threshold value

Figure 1

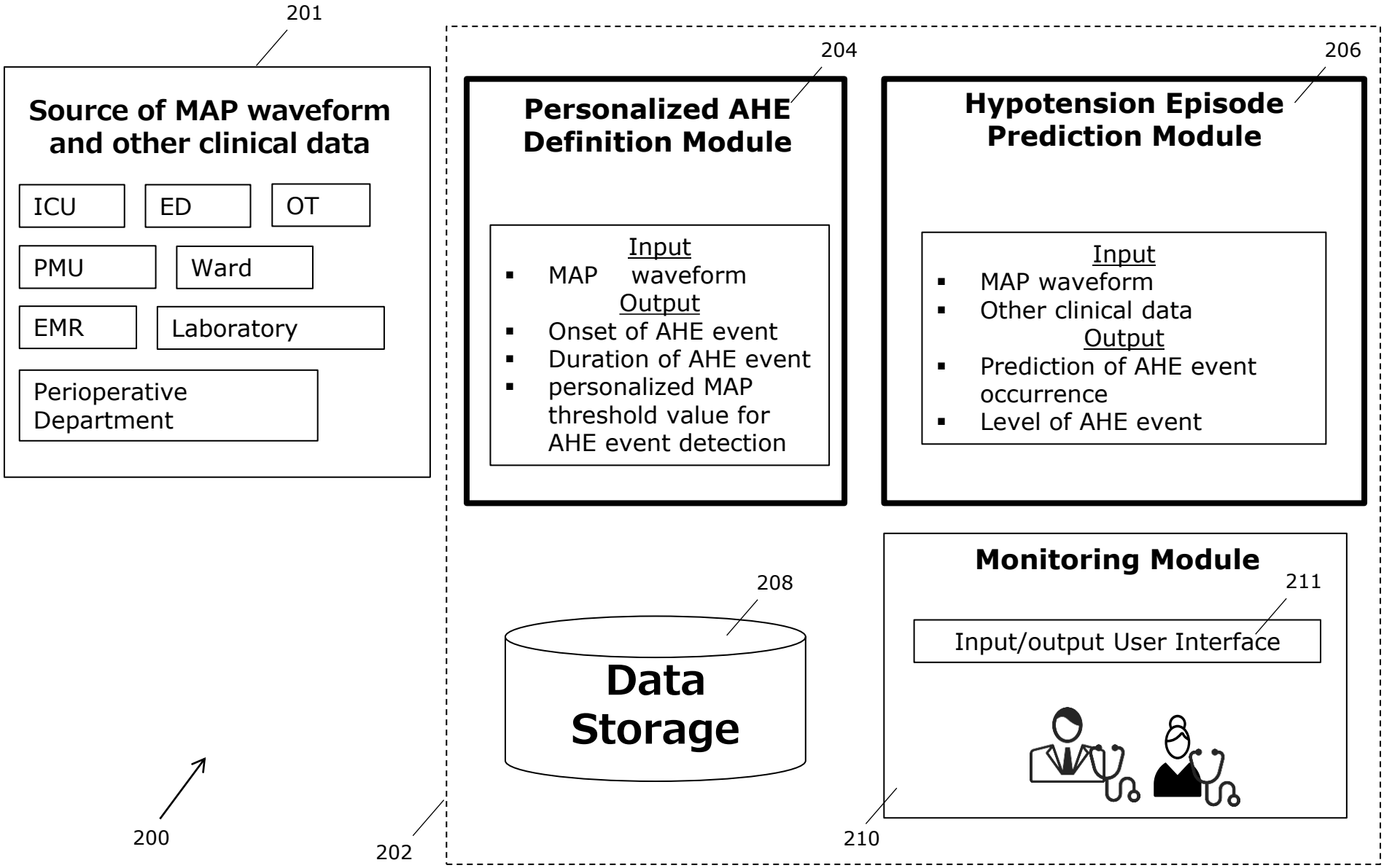

201
Source of MAP waveform and other clinical data
ICU
ED
OT
PMU
Ward
EMR
Laboratory
Perioperative Department
204
Personalized AHE Definition Module
Input
MAP waveform
Output
Onset of AHE event
Duration of AHE event
personalized MAP threshold value for AHE event detection
206
Hypotension Episode Prediction Module
Input
MAP waveform
Other clinical data
Output
Prediction of AHE event occurrence
Level of AHE event
208
Data Storage
Monitoring Module
211
Input/output User Interface
200
202
210

Figure 2

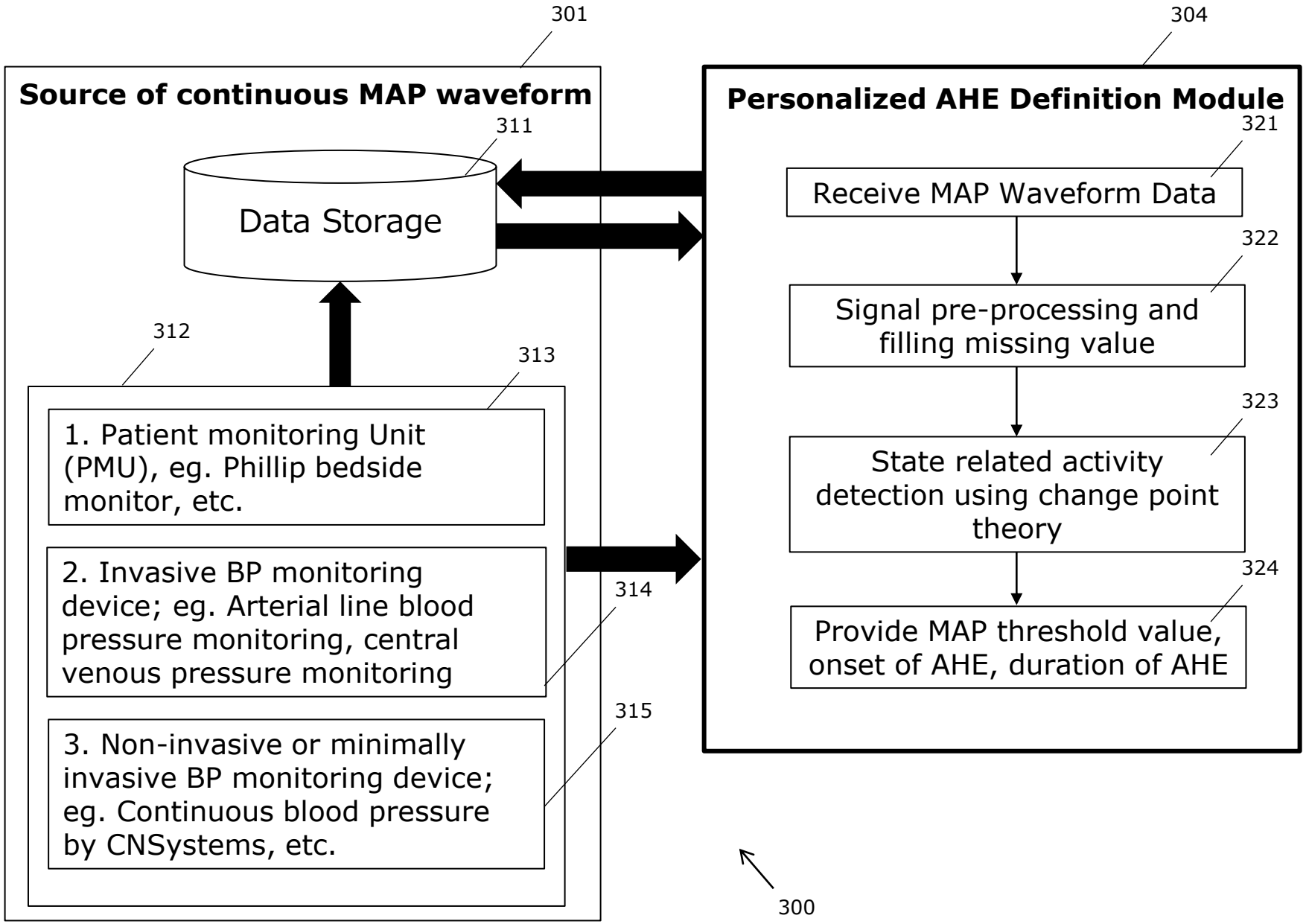

301
Source of continuous MAP waveform
311
Data Storage
312
313
1. Patient monitoring Unit (PMU), eg. Phillip bedside monitor, etc.
2. Invasive BP monitoring device; eg. Arterial line blood pressure monitoring, central venous pressure monitoring
314
3. Non-invasive or minimally invasive BP monitoring device; eg. Continuous blood pressure by CNSystems, etc.
315
304
Personalized AHE Definition Module
321
Receive MAP Waveform Data
322
Signal pre-processing and filling missing value
323
State related activity detection using change point theory
324
Provide MAP threshold value, onset of AHE, duration of AHE
300

Figure 3

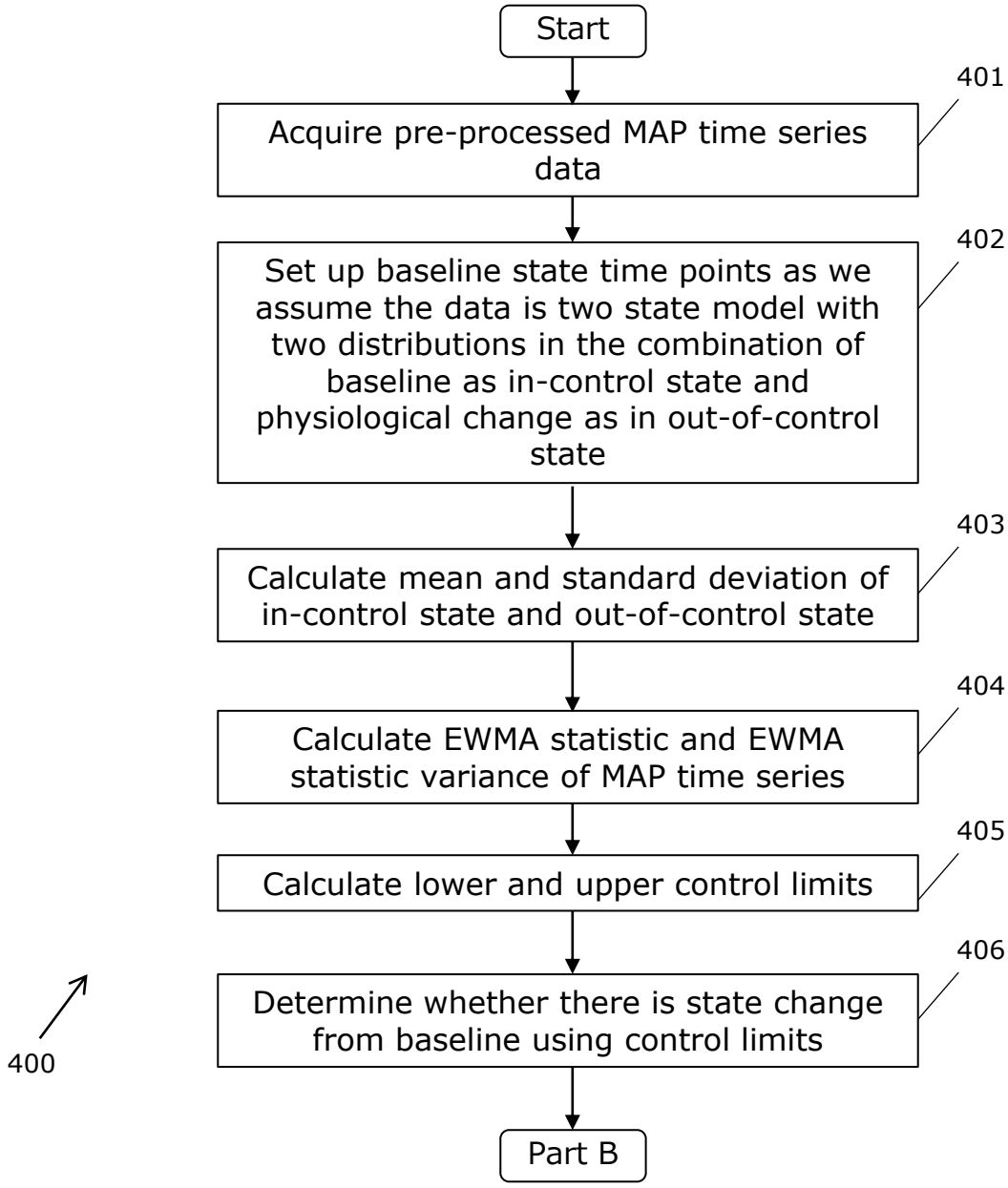

Start
401
Acquire pre-processed MAP time series data
402
Set up baseline state time points as we assume the data is two state model with two distributions in the combination of baseline as in-control state and physiological change as in out-of-control state
403
Calculate mean and standard deviation of in-control state and out-of-control state
404
Calculate EWMA statistic and EWMA statistic variance of MAP time series
405
Calculate lower and upper control limits
406
Determine whether there is state change from baseline using control limits
400
Part B

Figure 4

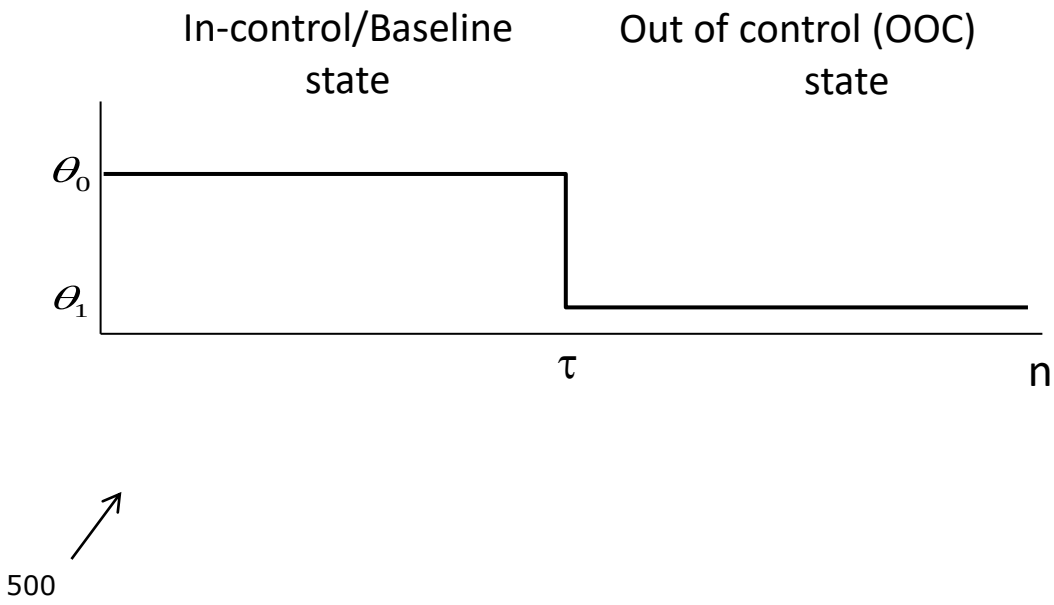

In-control/Baseline state
Out of control (OOC) state
θ_0
θ_1
τ
n
500

Figure 5

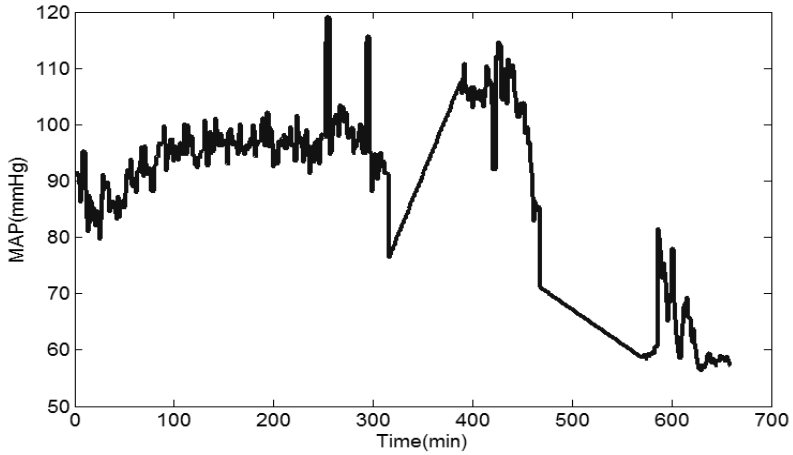


Figure 6A

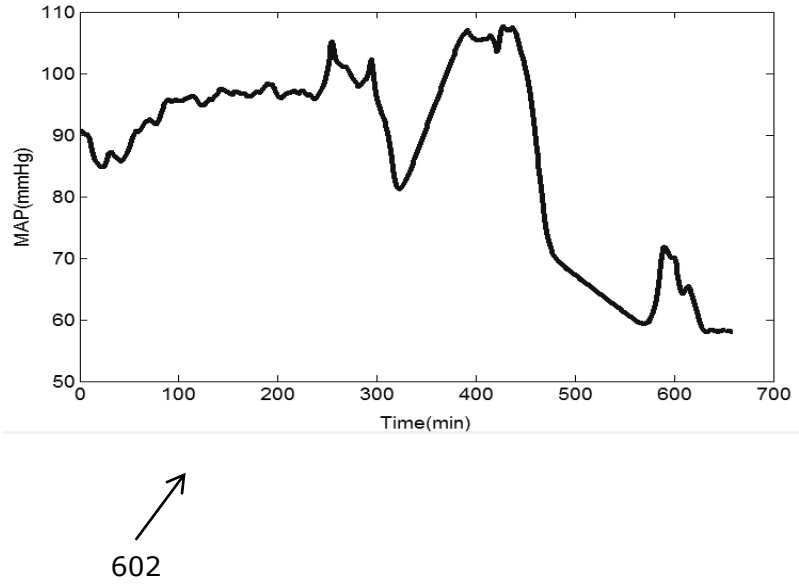


Figure 6B

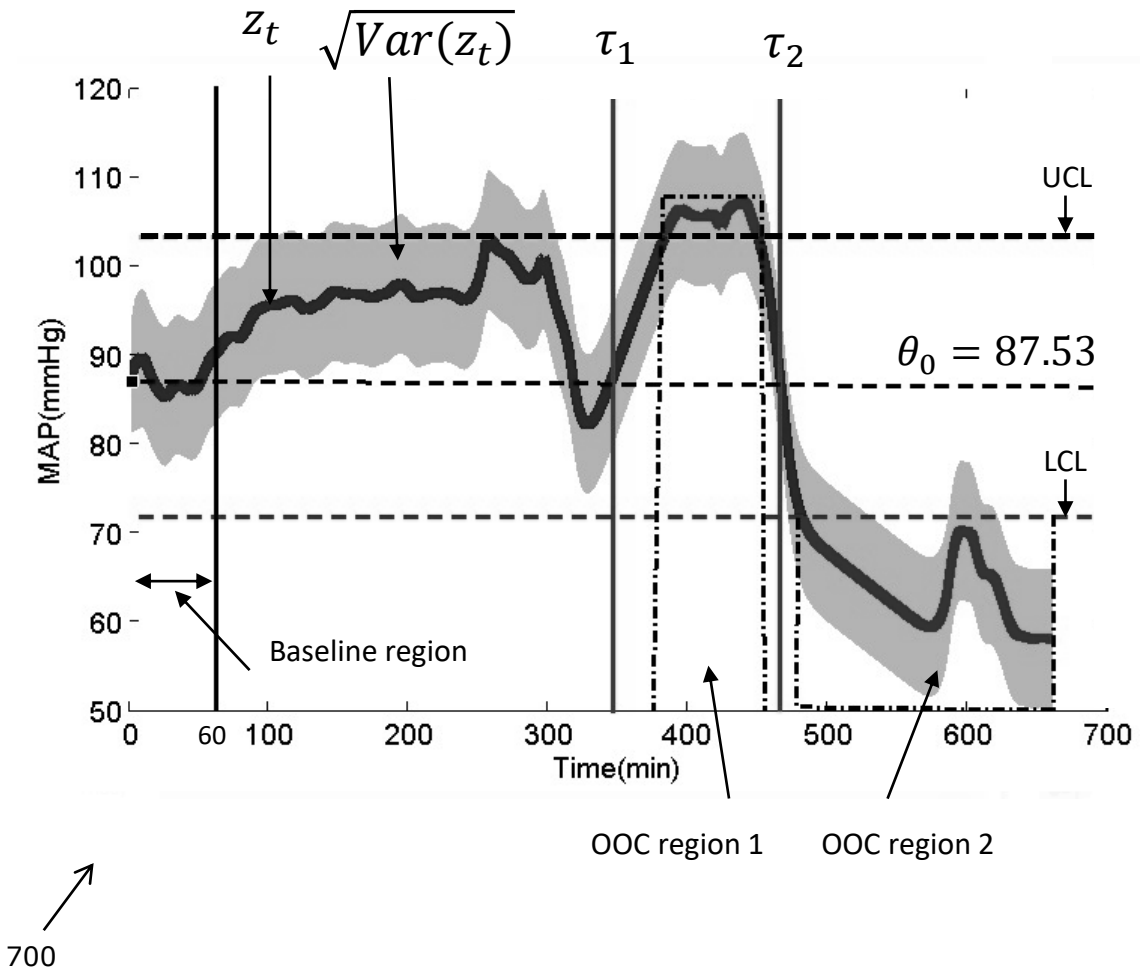

z_t
$\sqrt{Var(z_t)}$
τ_1
τ_2
UCL
$\theta_0 = 87.53$
LCL
MAP(mmHg)
120
110
100
90
80
70
60
50
0
60
100
200
300
400
500
600
700
Time(min)
Baseline region
OOC region 1
OOC region 2
700

Figure 7

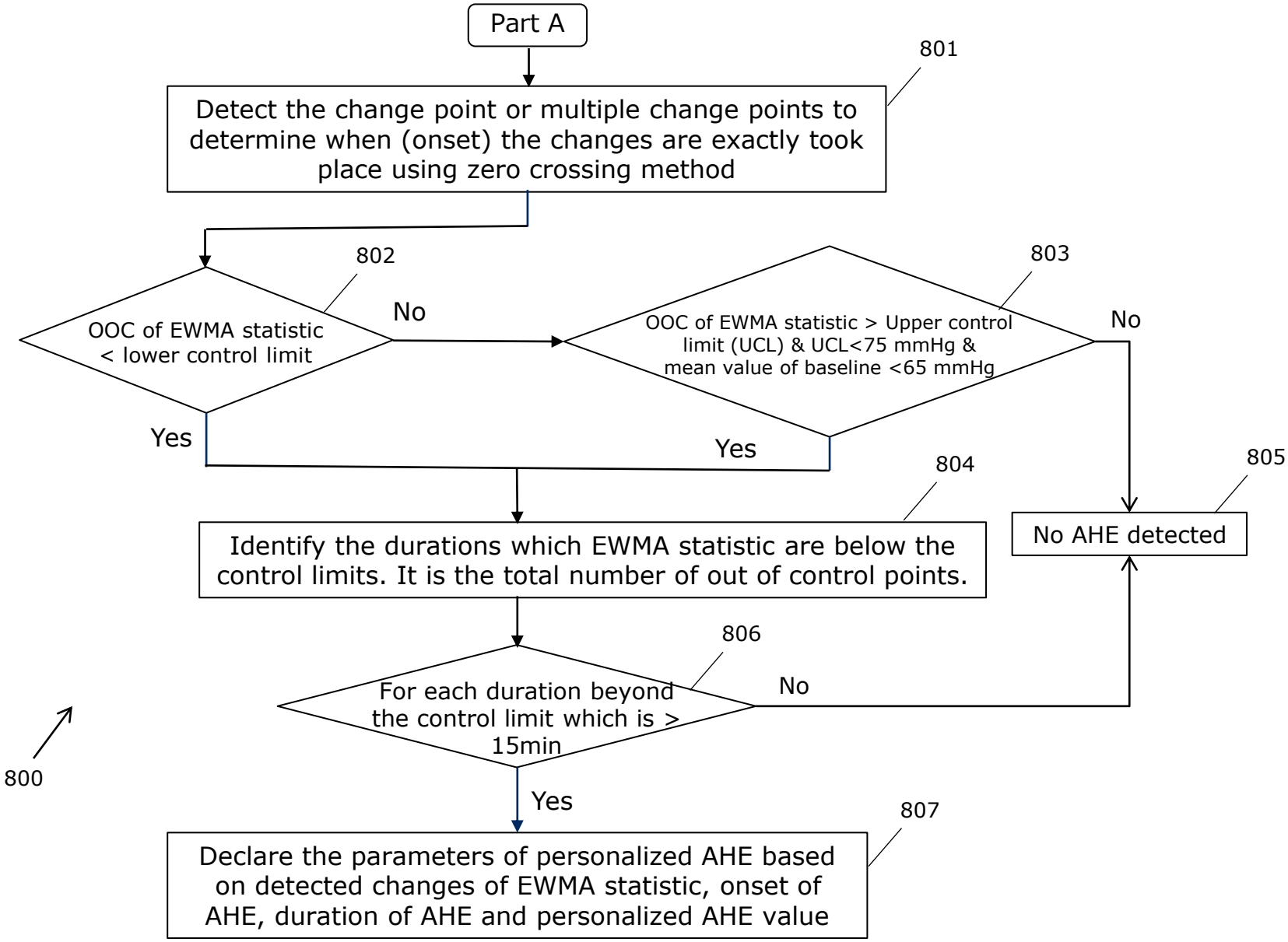

Part A
801
Detect the change point or multiple change points to determine when (onset) the changes are exactly took place using zero crossing method
802
OOC of EWMA statistic < lower control limit
No
803
OOC of EWMA statistic > Upper control limit (UCL) & UCL<75 mmHg & mean value of baseline <65 mmHg
No
Yes
Yes
804
Identify the durations which EWMA statistic are below the control limits. It is the total number of out of control points.
805
No AHE detected
806
For each duration beyond the control limit which is > 15min
No
Yes
807
Declare the parameters of personalized AHE based on detected changes of EWMA statistic, onset of AHE, duration of AHE and personalized AHE value
800

Figure 8

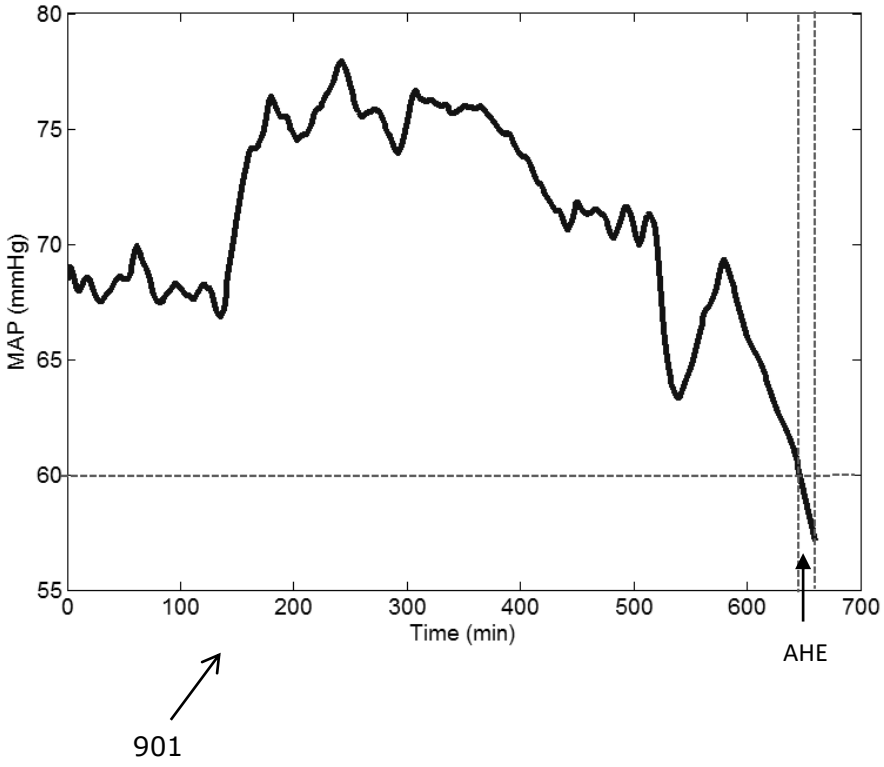


Figure 9A

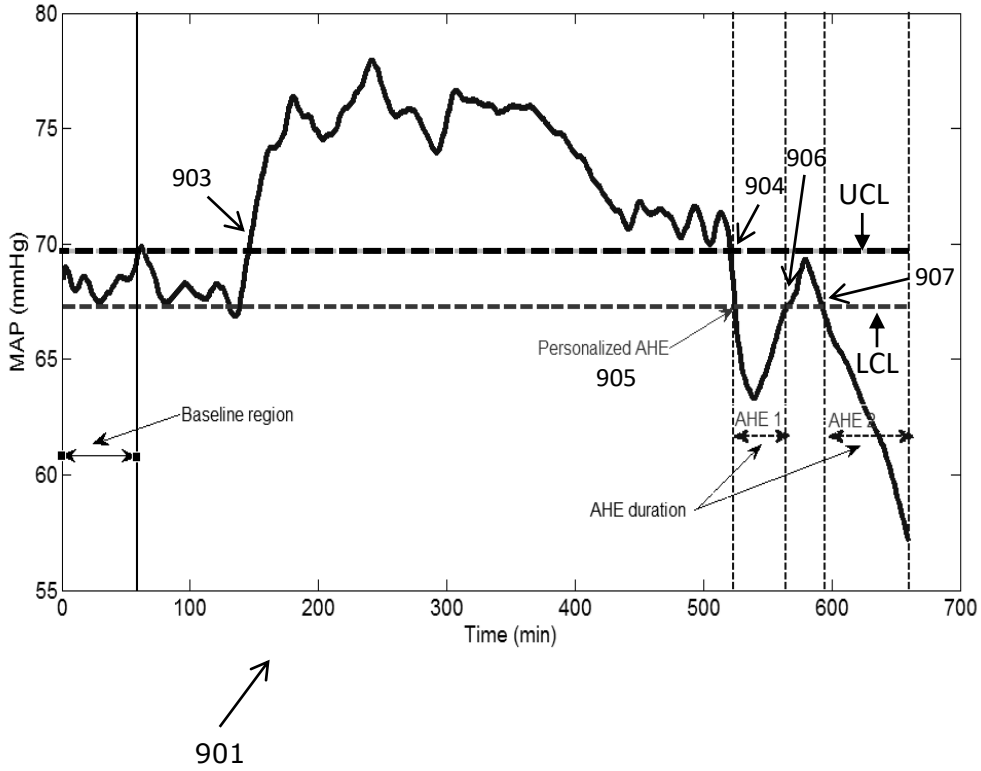


Figure 9B

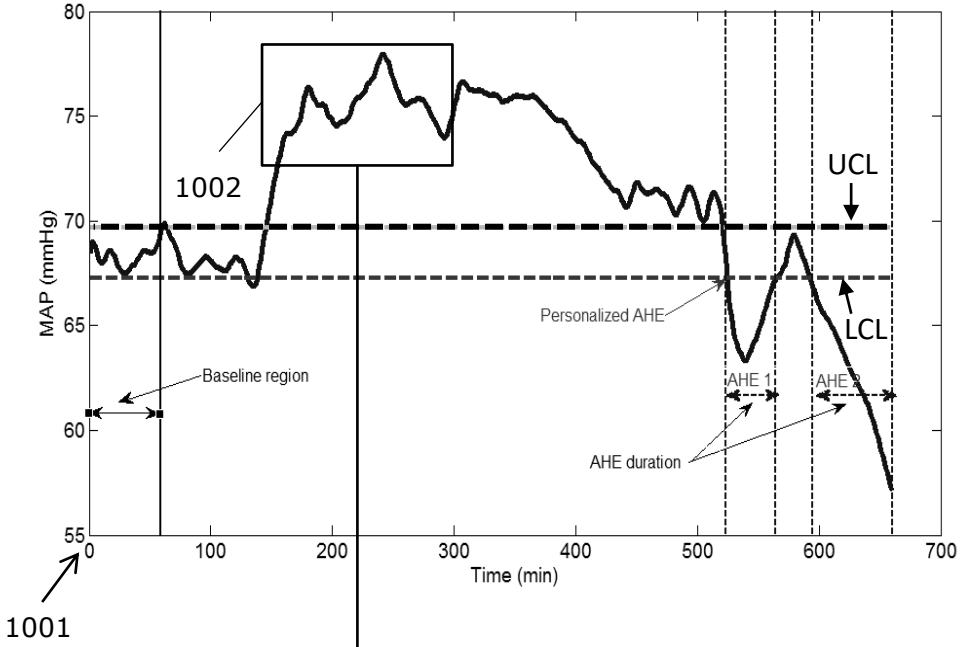


Figure 10A

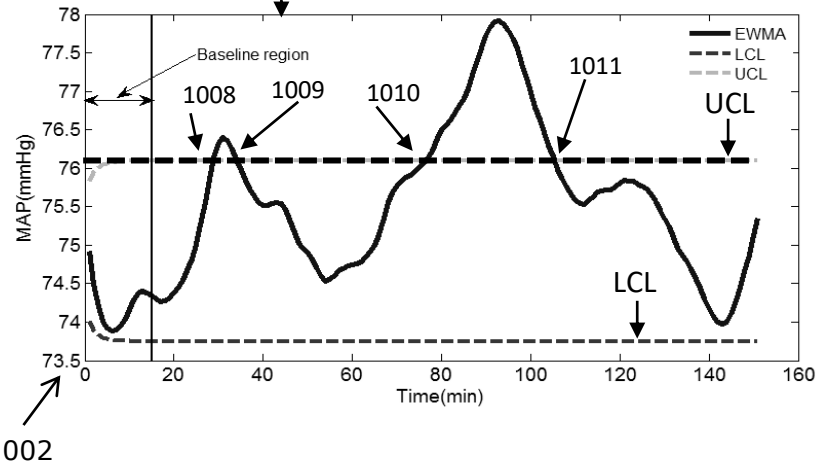


Figure 10B

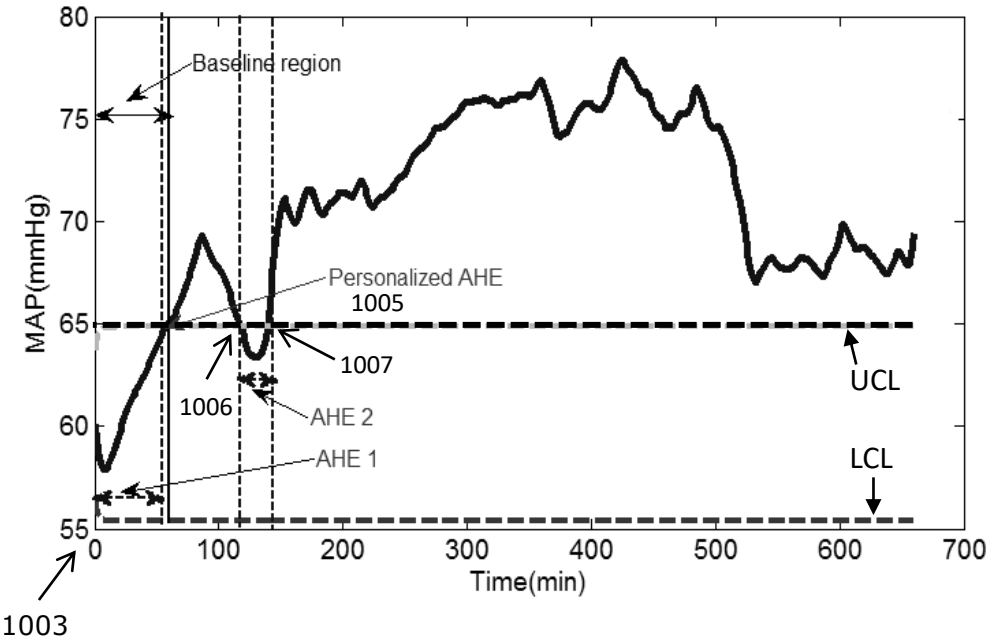


Figure 10C

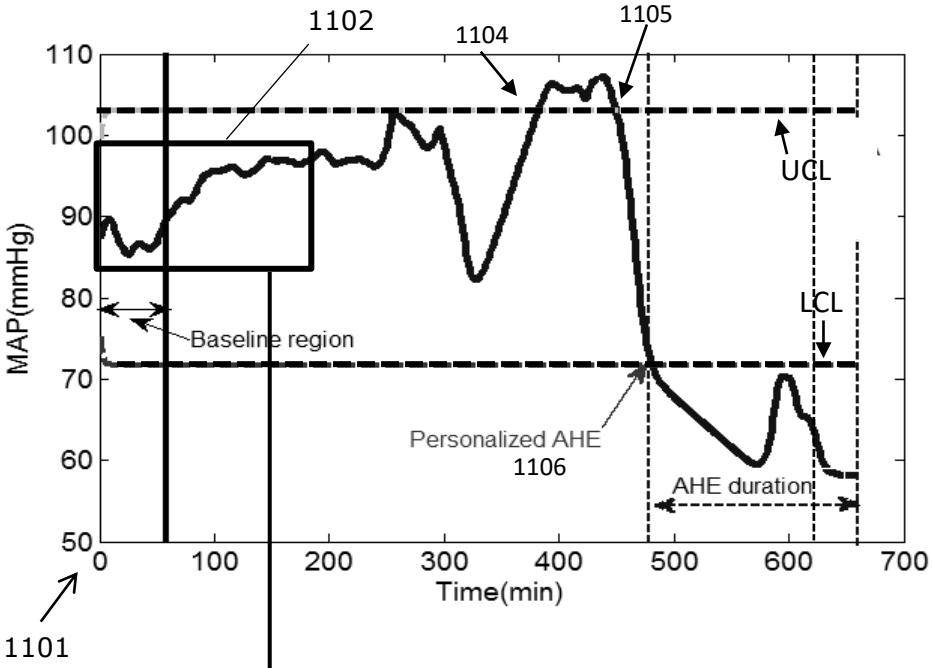


Figure 11A

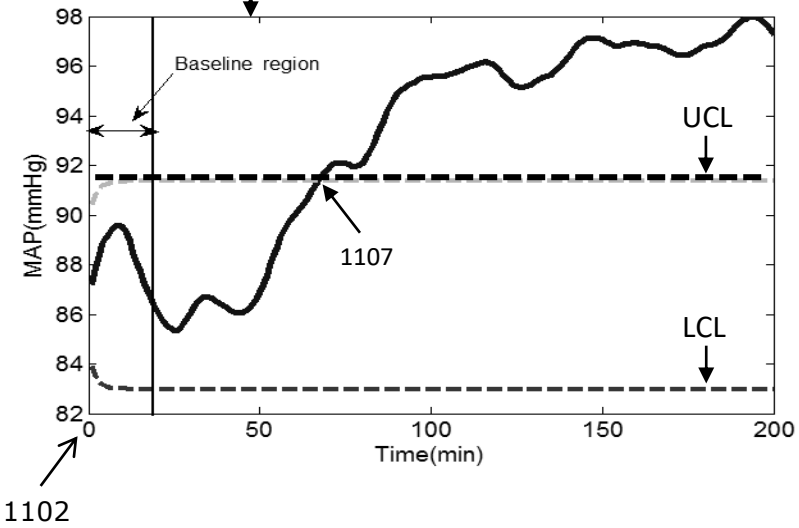


Figure 11B

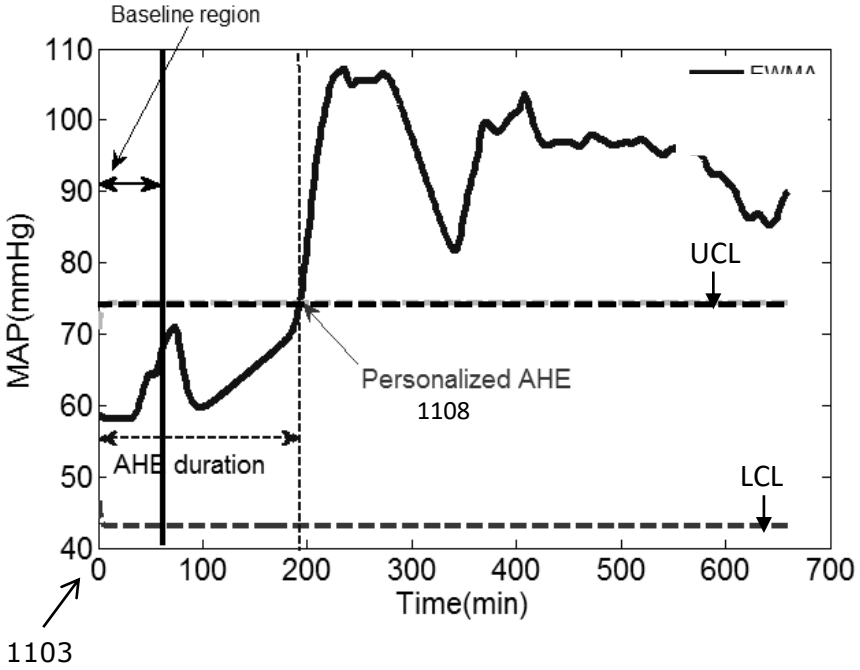


Figure 11C

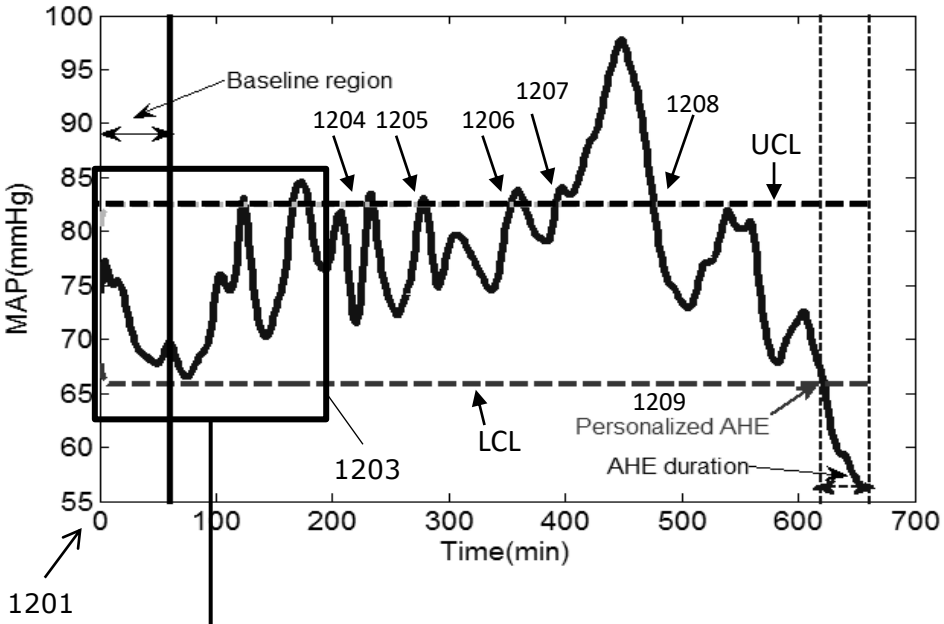


Figure 12A

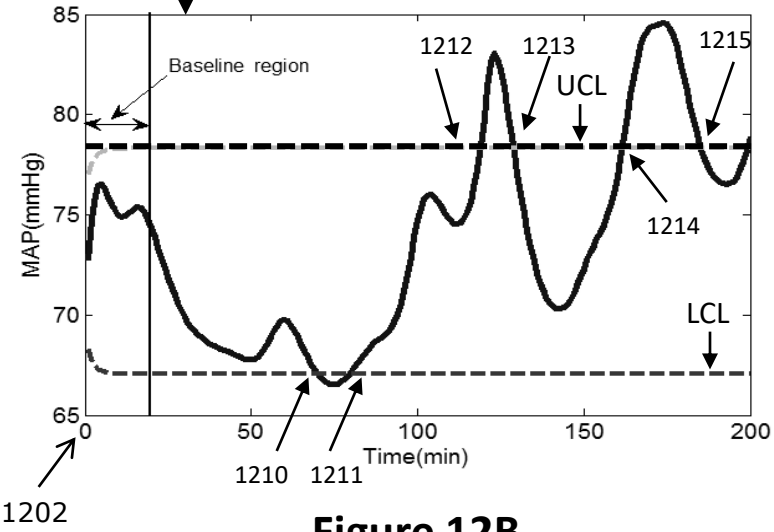


Figure 12B

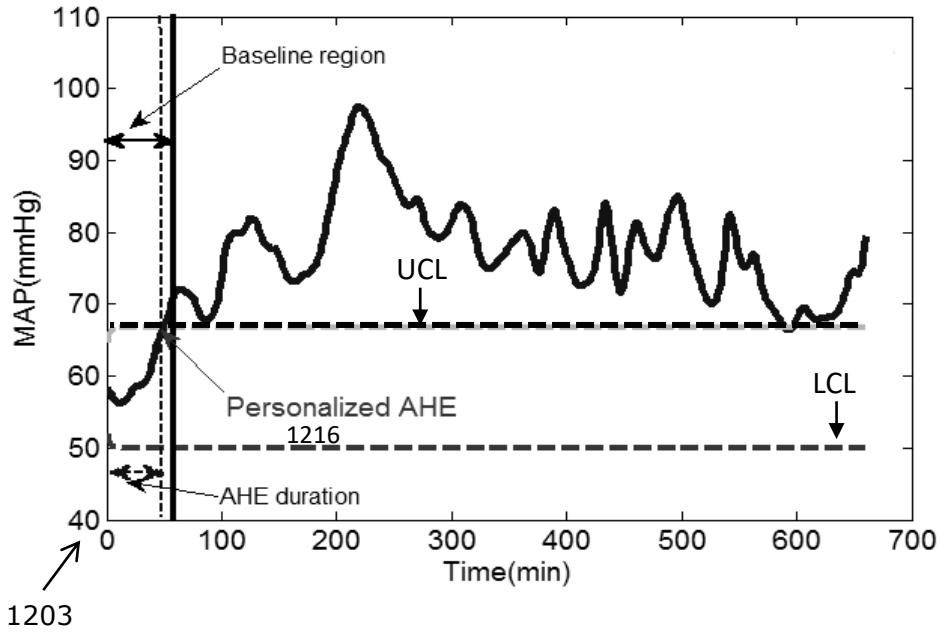
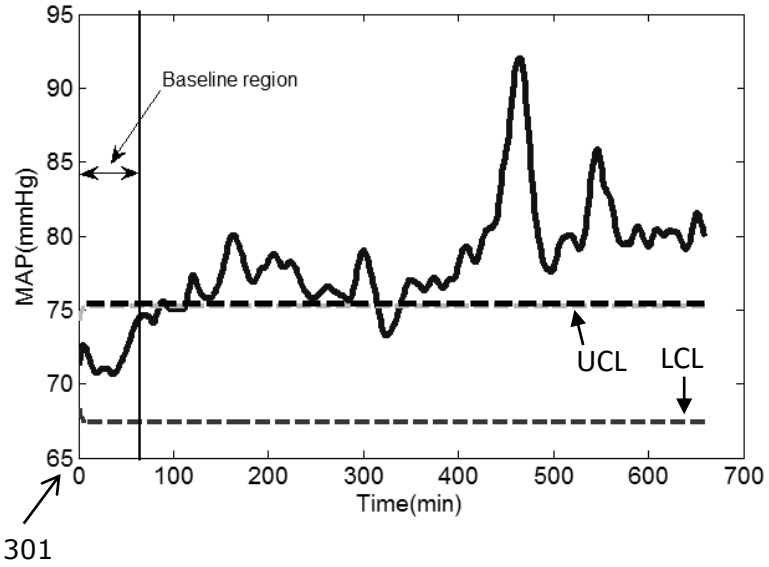
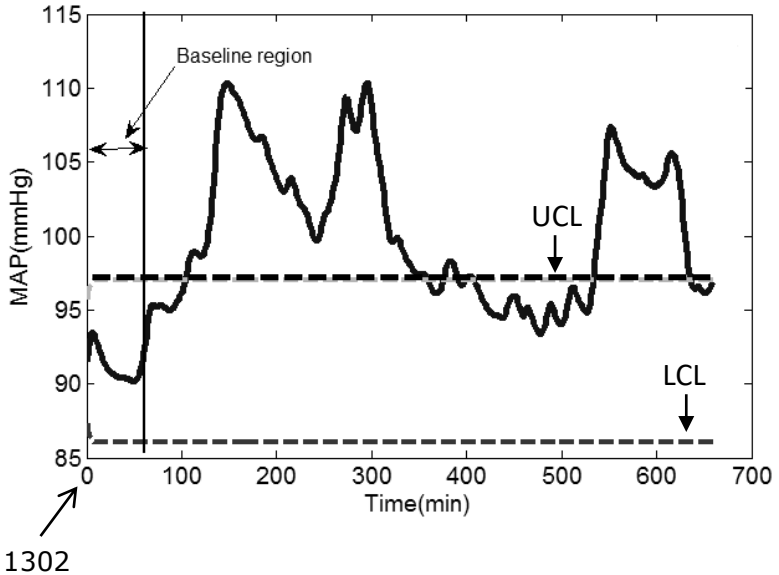


Figure 12C



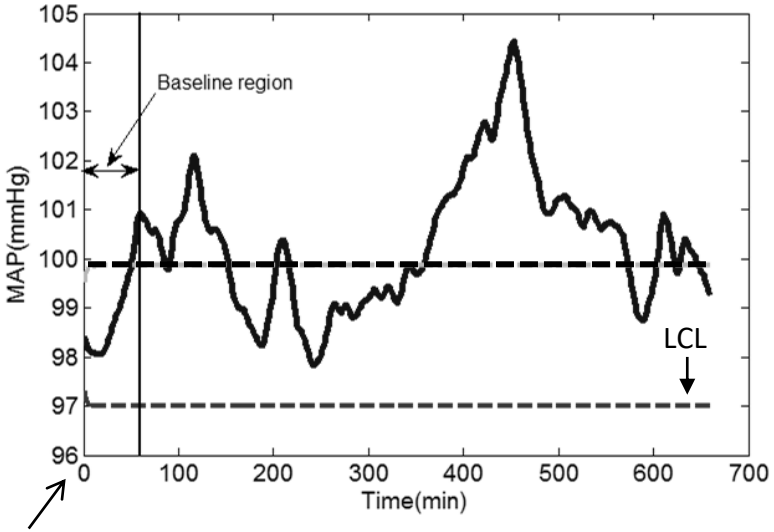
1301

Figure 13A



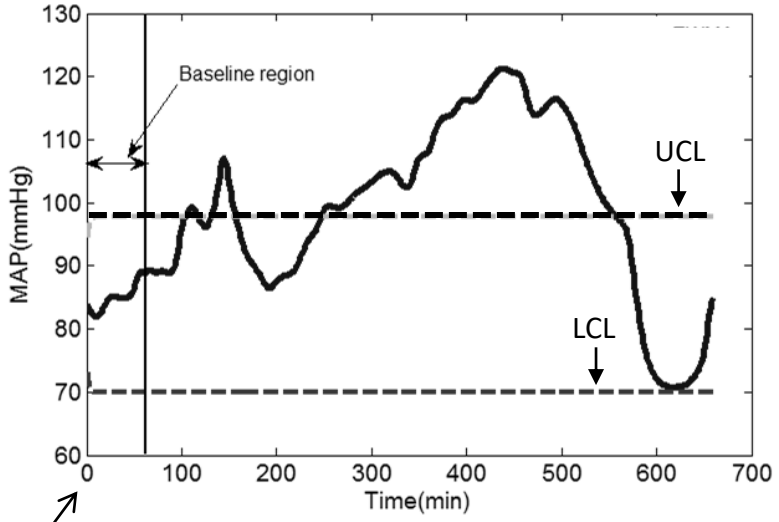
1302

Figure 13B



1303

Figure 13C



1304

Figure 13D

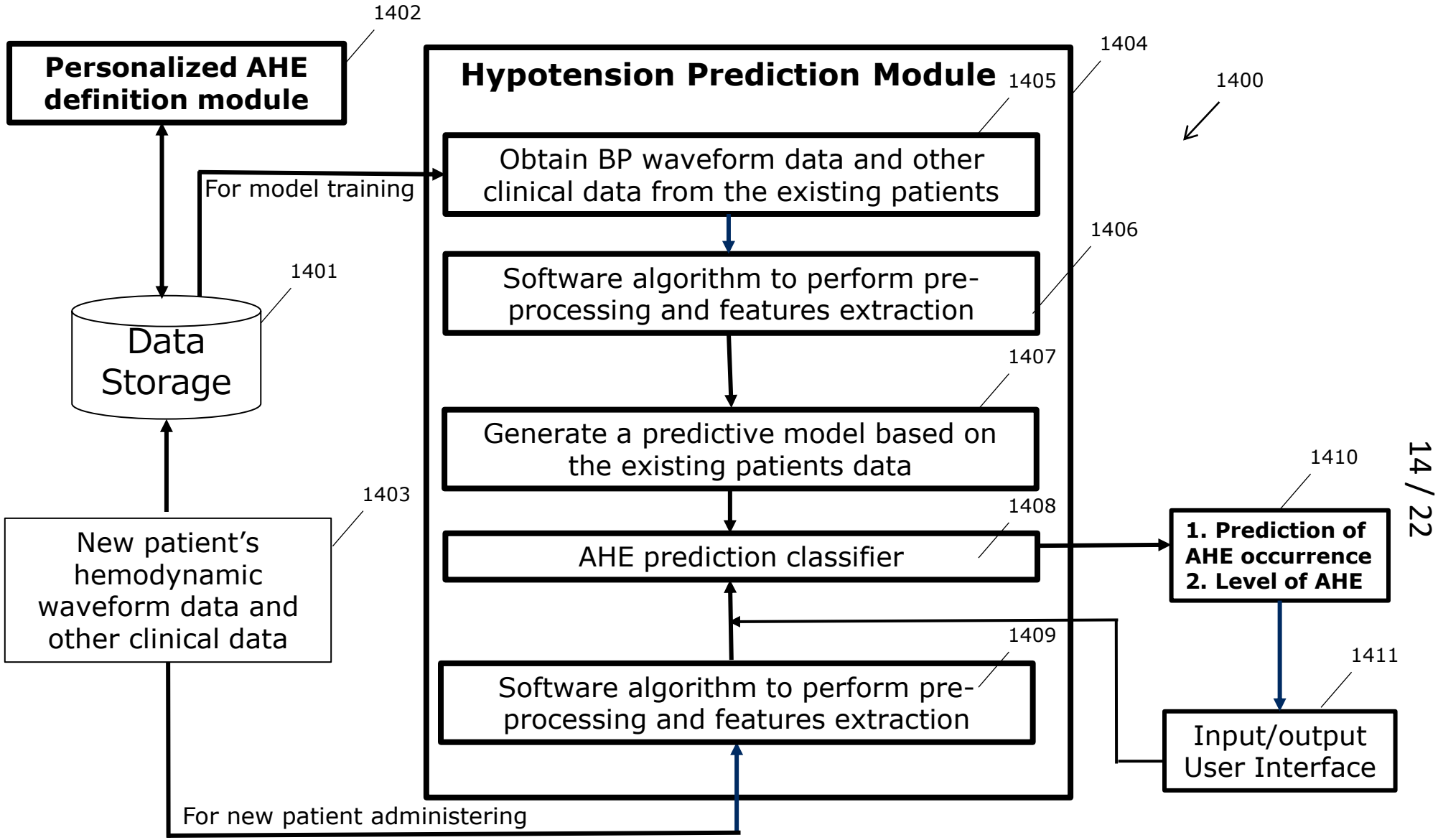

1402
Personalized AHE definition module
1404
Hypotension Prediction Module
1405
1400
Obtain BP waveform data and other clinical data from the existing patients
For model training
1406
Software algorithm to perform pre-processing and features extraction
1401
Data Storage
1407
Generate a predictive model based on the existing patients data
1410
1403
1408
New patient's hemodynamic waveform data and other clinical data
AHE prediction classifier
1. Prediction of AHE occurrence
2. Level of AHE
1409
1411
Software algorithm to perform pre-processing and features extraction
Input/output User Interface
For new patient administering

Figure 14

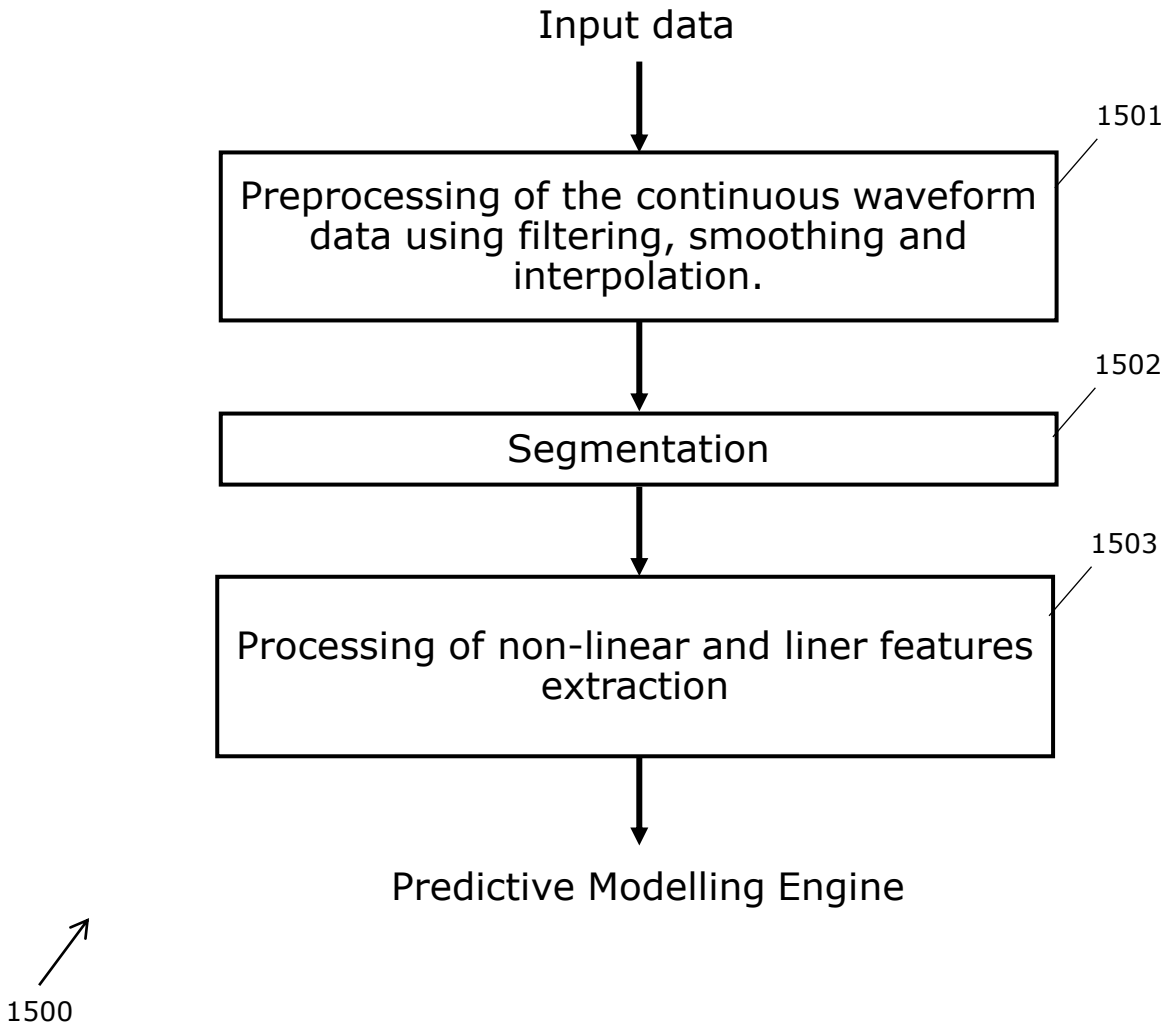

Input data
1501
Preprocessing of the continuous waveform data using filtering, smoothing and interpolation.
1502
Segmentation
1503
Processing of non-linear and liner features extraction
Predictive Modelling Engine
1500

Figure 15

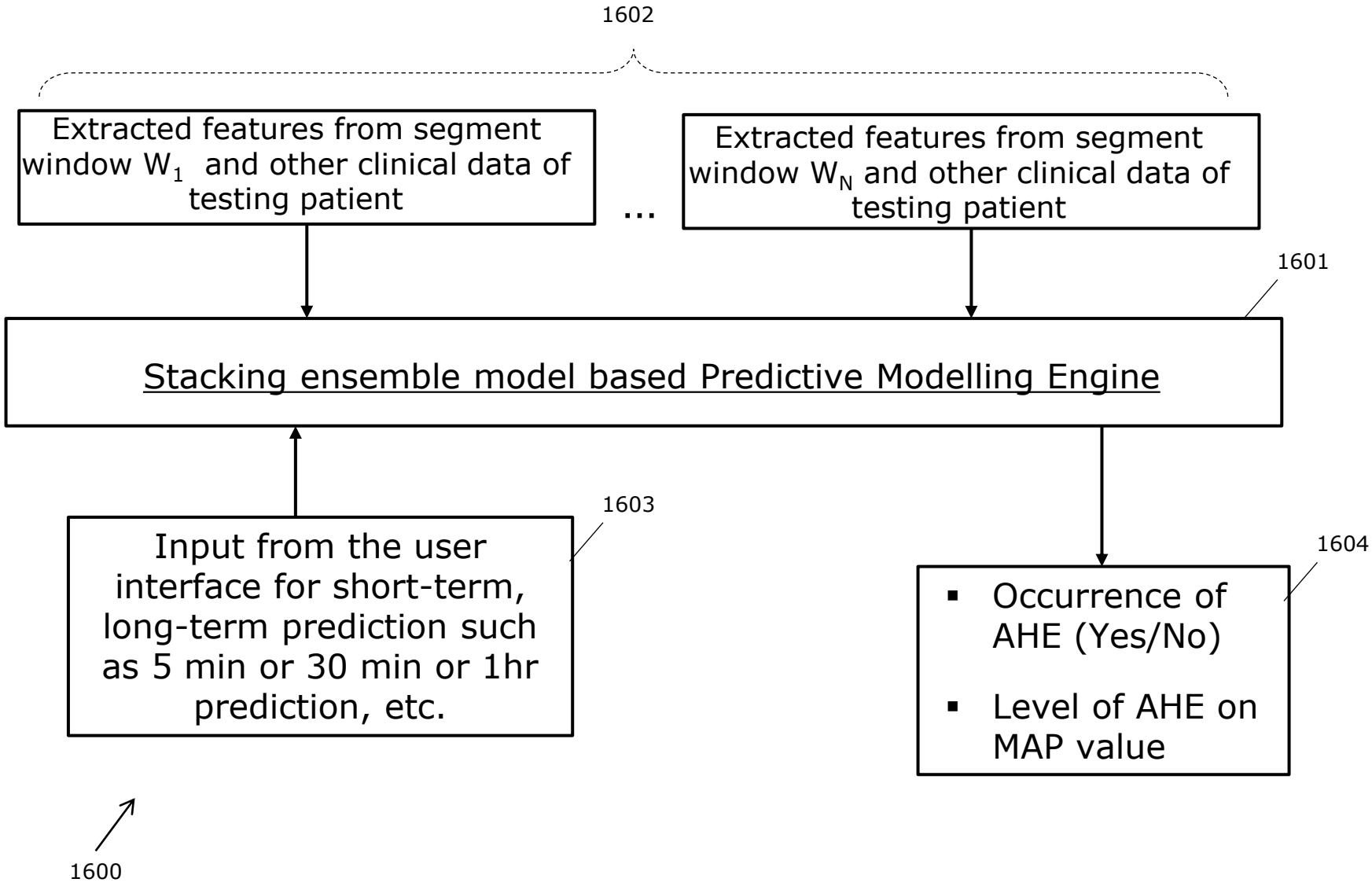
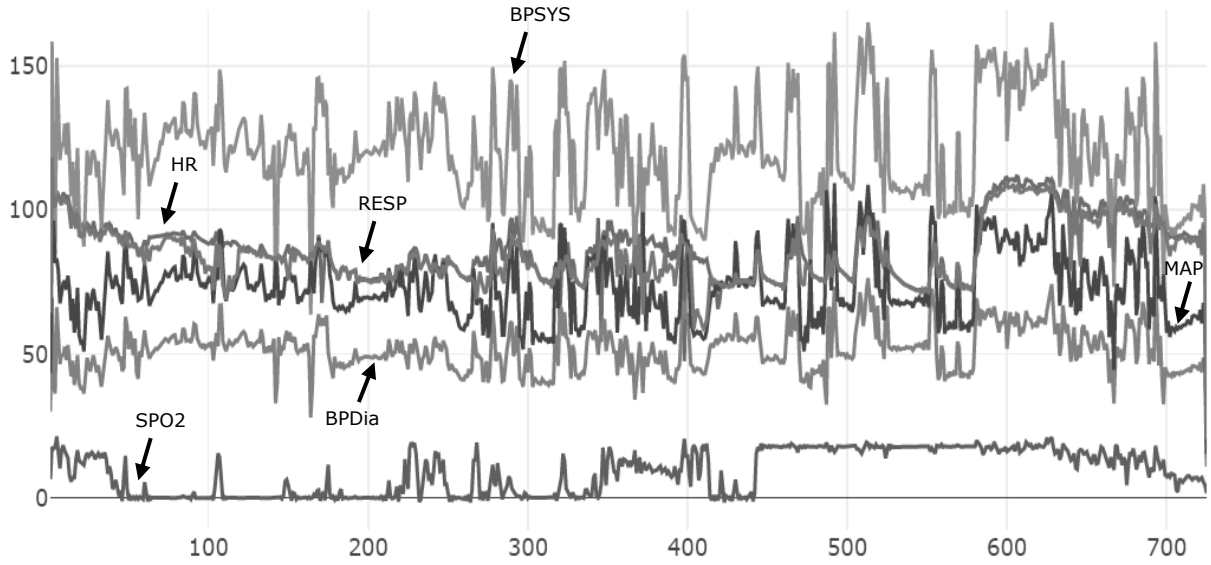

1602
Extracted features from segment window W_1 and other clinical data of testing patient
...
Extracted features from segment window W_N and other clinical data of testing patient
1601
Stacking ensemble model based Predictive Modelling Engine
1603
Input from the user interface for short-term, long-term prediction such as 5 min or 30 min or 1hr prediction, etc.
1604
Occurrence of AHE (Yes/No)
Level of AHE on MAP value
1600

Figure 16



BPSYS: Systolic blood pressure
HR: Hear rate
RESP: Respiratory rate
MAP: Mean arterial pressure
BPDia: Diastolic blood pressure
SPO2: Blood oxygen saturation

Figure 17A

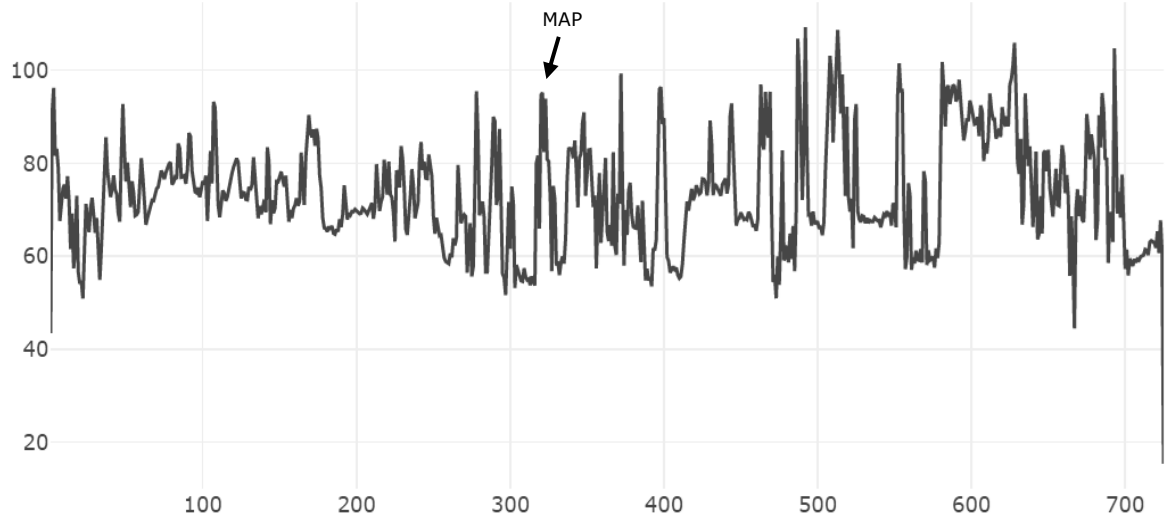
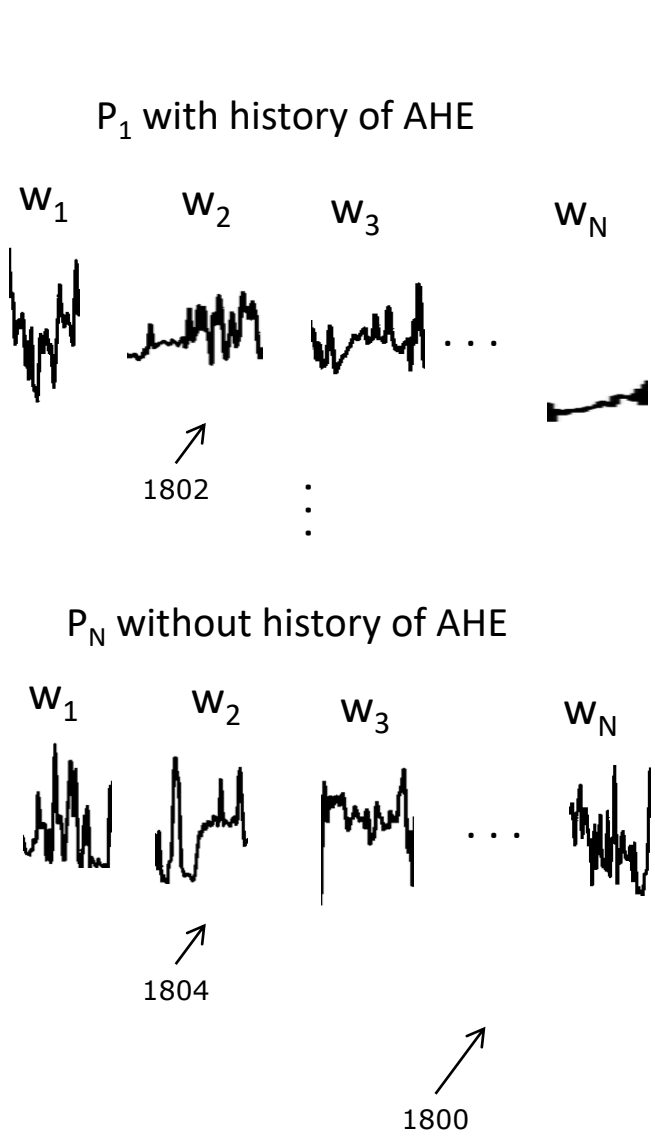


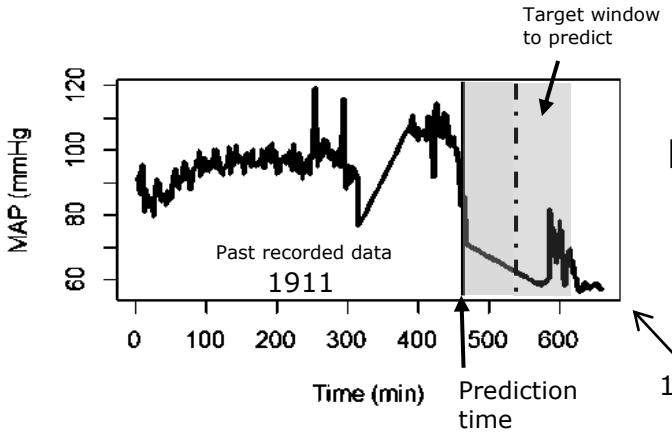
Figure 17B



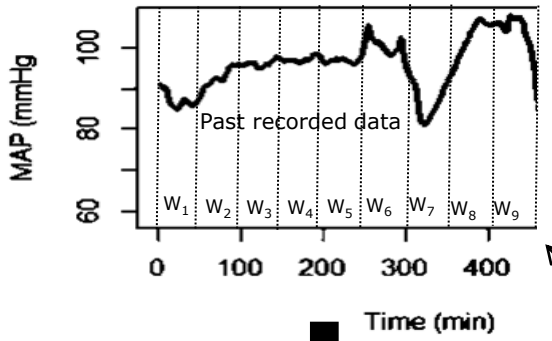
Pts	AHEleve	AHEons	channel	maxpw	meanpw	maxf	meanf	medianf	minf	freqRatio	maxAct	meanAc	minAct	varAct	maxWnd	meanWn	minWnd	varWnda	skewnes	kurtosis'	RMSWn	CrestFa	Coefficie
1	2	0	1	1.00	0.03	16.38	32.08	16.38	475.14	29.00	91.77	64.78	52.89	106.05	91.77	49.29	6.59	211.94	0.11	1.31	51.40	0.83	29.54
1	2	0	1	0.90	0.03	16.38	34.78	24.58	434.18	26.50	82.04	62.15	52.89	31.60	82.04	54.29	18.73	109.31	-0.27	-0.11	55.29	0.57	19.26
1	2	0	1	0.09	0.00	16.38	32.85	16.38	450.56	27.50	69.75	60.15	52.95	20.51	69.75	15.60	8.26	115.78	3.40	11.13	18.95	1.62	68.99
1	2	0	1	1.03	0.03	16.38	32.85	16.38	491.52	30.00	83.13	62.37	52.89	53.50	83.13	50.61	21.51	137.23	0.22	-0.02	51.95	0.59	23.15
1	2	0	1	0.77	0.03	16.38	33.72	24.58	491.52	30.00	77.41	60.27	52.89	27.91	77.41	47.47	8.97	200.10	-0.93	0.65	49.53	0.69	29.80
1	2	0	1	0.17	0.01	16.38	31.81	16.38	491.52	30.00	66.17	62.79	59.43	3.69	66.17	15.14	4.07	261.06	1.79	1.63	22.14	1.40	106.71
1	2	0	1	1.14	0.04	16.38	31.20	16.38	466.94	28.50	98.57	69.26	59.38	66.62	98.57	55.81	7.18	433.24	-1.06	0.47	59.56	0.77	37.30
1	2	0	1	0.14	0.00	16.38	32.21	16.38	450.56	27.50	61.83	60.45	59.47	0.41	61.83	15.46	5.62	189.72	2.17	3.47	20.70	1.36	89.10
1	2	0	1	0.94	0.03	16.38	33.85	24.58	483.33	29.50	97.23	73.74	59.39	82.70	97.23	61.21	7.61	391.10	-0.98	0.86	64.32	0.70	32.31
1	2	1	1	1.52	0.05	16.38	31.59	16.38	483.33	29.50	100.00	70.40	59.38	71.75	100.00	64.96	21.58	152.91	-0.36	1.28	66.13	0.59	19.03
1	2	1	1	1.07	0.03	16.38	31.05	16.38	458.75	28.00	79.66	61.75	53.47	34.93	79.66	53.77	7.30	189.07	-1.70	3.87	55.50	0.65	25.57
1	2	0	2	1.19	0.03	16.38	29.25	16.38	499.71	30.50	95.94	64.26	53.47	62.52	95.94	50.70	13.93	266.94	-0.26	-0.44	53.27	0.77	32.23
1	2	0	2	0.61	0.02	16.38	32.57	24.58	475.14	29.00	89.32	60.57	53.48	58.55	89.32	47.63	19.89	93.59	0.97	2.16	48.60	0.71	20.31
1	2	0	2	0.92	0.03	16.38	32.67	16.38	425.98	26.00	100.00	67.69	58.76	54.80	100.00	58.60	25.95	141.25	-0.05	0.53	59.80	0.62	20.28
1	2	0	2	0.67	0.02	16.38	35.43	24.58	499.71	30.50	92.73	67.86	58.75	44.57	92.73	60.55	13.29	209.60	-1.29	1.97	62.25	0.64	23.91
1	2	0	2	0.68	0.03	16.38	35.19	24.58	499.71	30.50	96.44	70.53	58.75	68.32	96.44	58.56	6.72	387.20	-0.97	0.42	61.78	0.73	33.60
1	2	0	2	0.12	0.00	16.38	33.41	24.58	434.18	26.50	79.47	66.23	58.78	24.71	79.47	18.51	5.57	323.53	1.88	2.03	25.81	1.43	97.18
1	2	0	2	0.79	0.03	16.38	34.94	16.38	466.94	28.50	91.07	68.19	55.43	51.28	91.07	56.60	5.33	534.30	-1.30	0.35	61.14	0.70	40.84
1	2	0	2	0.22	0.01	16.38	31.87	16.38	458.75	28.00	75.57	63.18	55.44	21.06	75.57	16.34	4.78	261.71	2.11	3.17	22.99	1.54	99.00
1	2	0	2	0.43	0.01	16.38	34.79	24.58	458.75	28.00	75.58	63.26	55.42	39.38	75.58	42.60	7.24	211.40	-0.65	0.74	45.01	0.76	34.13
1	2	1	2	0.48	0.02	16.38	35.95	24.58	491.52	30.00	77.07	64.48	55.42	29.00	77.07	46.78	8.84	186.99	-0.30	0.53	48.74	0.70	29.23
1	2	1	2	1.03	0.03	16.38	32.65	16.38	466.94	28.50	86.75	65.15	55.41	43.73	86.75	58.91	10.33	123.23	-0.76	1.98	59.95	0.64	18.84

Pts	AHEleve	AHEons	channel	maxpw	meanpw	maxf	meanf	medianf	minf	freqRatio	maxAct	meanAc	minAct	varAct	maxWnd	meanWn	minWnd	varWnda	skewnes	kurtosis'	RMSWn	CrestFa	Coefficie
2	5	0	1	0.84	0.03	16.38	34.05	24.58	483.33	29.50	95.61	64.20	52.19	69.58	95.61	59.70	15.07	142.38	-0.41	1.30	60.88	0.66	19.99
2	5	0	1	0.04	0.00	16.38	32.79	24.58	458.75	28.00	53.06	52.78	52.47	0.06	53.06	10.94	5.15	69.06	2.89	8.01	13.74	1.74	75.98
2	5	0	1	1.16	0.03	16.38	30.50	16.38	466.94	28.50	100.00	63.37	52.16	90.71	100.00	55.97	16.33	188.35	-0.13	0.79	57.63	0.73	24.52
2	5	0	1	0.06	0.00	16.38	28.92	16.38	491.52	30.00	65.60	56.84	52.24	8.65	65.60	10.77	5.28	129.35	3.40	10.20	15.66	1.93	105.58
2	5	0	1	0.97	0.03	16.38	29.74	16.38	499.71	30.50	78.43	63.36	52.16	42.63	78.43	48.22	11.18	194.58	-0.15	-0.20	50.20	0.67	28.93
2	5	0	1	1.43	0.04	16.38	30.19	16.38	491.52	30.00	97.23	73.31	61.25	91.97	97.23	61.35	17.73	219.61	0.02	-0.04	63.12	0.63	24.15
2	5	0	1	0.10	0.00	16.38	29.79	16.38	442.37	27.00	72.53	66.70	61.30	5.80	72.53	16.20	7.86	120.09	3.10	9.35	19.56	1.65	67.63
2	5	0	1	1.01	0.03	16.38	32.72	16.38	475.14	29.00	100.00	71.89	61.25	60.18	100.00	59.90	22.02	211.42	-0.31	0.08	61.64	0.63	24.27
2	5	0	1	0.07	0.00	16.38	31.50	16.38	499.71	30.50	74.89	67.92	61.26	27.70	74.89	14.05	5.70	146.38	3.08	9.18	18.54	1.87	86.11
2	5	0	1	0.89	0.03	16.38	33.83	16.38	483.33	29.50	88.69	69.53	61.24	36.90	88.69	60.76	19.79	135.07	-0.76	1.28	61.86	0.56	19.13
2	5	0	2	0.66	0.02	16.38	34.09	16.38	499.71	30.50	89.94	67.96	56.29	56.87	89.94	51.65	4.31	360.06	-0.91	0.74	55.02	0.78	36.74
2	5	0	2	0.78	0.03	16.38	34.60	16.38	499.71	30.50	88.70	66.03	56.27	42.69	88.70	60.45	12.77	123.11	-0.81	1.73	61.46	0.62	18.36
2	5	0	2	1.18	0.03	16.38	32.37	16.38	466.94	28.50	100.00	68.88	56.27	75.60	100.00	62.61	20.18	185.26	-0.55	0.74	64.07	0.62	21.74
2	5	0	2	0.66	0.02	16.38	35.23	24.58	450.56	27.50	83.61	65.09	56.27	32.96	83.61	56.80	24.13	145.92	-0.68	0.16	58.07	0.51	21.27
2	5	0	2	0.66	0.02	16.38	31.72	16.38	499.71	30.50	70.19	56.07	51.94	12.57	70.19	45.42	6.42	135.71	-1.67	3.44	46.89	0.68	25.65
2	5	0	2	0.05	0.00	16.38	33.28	24.58	466.94	28.50	51.97	51.96	51.94	0.00	51.97	11.93	6.36	70.52	3.05	9.24	14.59	1.56	70.39
2	5	0	2	0.61	0.02	16.38	31.84	16.38	442.37	27.00	62.16	55.73	51.95	9.48	62.16	41.23	16.33	62.90	-0.46	0.74	41.99	0.55	19.24
2	5	0	2	0.83	0.03	16.38	33.79	16.38	499.71	30.50	81.34	61.30	51.94	40.13	81.34	55.50	19.45	119.99	-0.72	0.87	56.57	0.55	19.74
2	5	0	2	0.11	0.00	16.38	28.52	16.38	458.75	28.00	54.15	52.95	51.96	0.47	54.15	13.70	7.09	83.51	2.81	7.06	16.47	1.43	66.70

Figure 18



1902



1904

window	maxpw	meanpw	maxf	meanf	medianf	minf	freqRatio	maxAct	meanAct	minAct	varAct
1	1.00	0.03	16.38	32.08	16.38	475.14	29.00	91.77	64.78	52.89	106.05
2	0.90	0.03	16.38	34.78	24.58	434.18	26.50	82.04	62.15	52.89	31.60
3	0.09	0.00	16.38	32.85	16.38	450.56	27.50	69.75	60.15	52.95	20.51
4	1.03	0.03	16.38	32.85	16.38	491.52	30.00	83.13	62.37	52.89	53.50
5	0.77	0.03	16.38	33.72	24.58	491.52	30.00	77.41	60.27	52.89	27.91
6	0.17	0.01	16.38	31.81	16.38	491.52	30.00	66.17	62.79	59.43	3.69
7	1.14	0.04	16.38	31.20	16.38	466.94	28.50	98.57	69.26	59.38	66.62
8	0.14	0.00	16.38	32.21	16.38	450.56	27.50	61.83	60.45	59.47	0.41
9	0.94	0.03	16.38	33.85	24.58	483.33	29.50	97.23	73.74	59.39	82.70

1908

window	maxpw	meanpw	maxf	meanf	medianf	minf	freqRatio	maxAct	meanAct	minAct	varAct
1	1.00	0.03	16.38	32.08	16.38	475.14	29.00	91.77	64.78	52.89	106.05
2	0.90	0.03	16.38	34.78	24.58	434.18	26.50	82.04	62.15	52.89	31.60
3	0.09	0.00	16.38	32.85	16.38	450.56	27.50	69.75	60.15	52.95	20.51
4	1.03	0.03	16.38	32.85	16.38	491.52	30.00	83.13	62.37	52.89	53.50
5	0.77	0.03	16.38	33.72	24.58	491.52	30.00	77.41	60.27	52.89	27.91
6	0.17	0.01	16.38	31.81	16.38	491.52	30.00	66.17	62.79	59.43	3.69
7	1.14	0.04	16.38	31.20	16.38	466.94	28.50	98.57	69.26	59.38	66.62
8	0.14	0.00	16.38	32.21	16.38	450.56	27.50	61.83	60.45	59.47	0.41
9	0.94	0.03	16.38	33.85	24.58	483.33	29.50	97.23	73.74	59.39	82.70

window	maxpw	meanpw	maxf	meanf	medianf	minf	freqRatio	maxAct	meanAct	minAct	varAct
1	1.00	0.03	16.38	32.08	16.38	475.14	29.00	91.77	64.78	52.89	106.05
2	0.90	0.03	16.38	34.78	24.58	434.18	26.50	82.04	62.15	52.89	31.60
3	0.09	0.00	16.38	32.85	16.38	450.56	27.50	69.75	60.15	52.95	20.51
4	1.03	0.03	16.38	32.85	16.38	491.52	30.00	83.13	62.37	52.89	53.50
5	0.77	0.03	16.38	33.72	24.58	491.52	30.00	77.41	60.27	52.89	27.91
6	0.17	0.01	16.38	31.81	16.38	491.52	30.00	66.17	62.79	59.43	3.69
7	1.14	0.04	16.38	31.20	16.38	466.94	28.50	98.57	69.26	59.38	66.62
8	0.14	0.00	16.38	32.21	16.38	450.56	27.50	61.83	60.45	59.47	0.41
9	0.94	0.03	16.38	33.85	24.58	483.33	29.50	97.23	73.74	59.39	82.70

Time dependent Features Extraction

Compute the following features from each window:

maximum power, mean power, min power, maximum frequency, mean frequency, median frequency, minimum frequency, maximum of segmented data, mean of segmented data, minimum of segmented data, variance of segmented data, skewness of segmented data, kurtosis of segmented data, RMS value of segmented data and etc.

1906

Figure 19

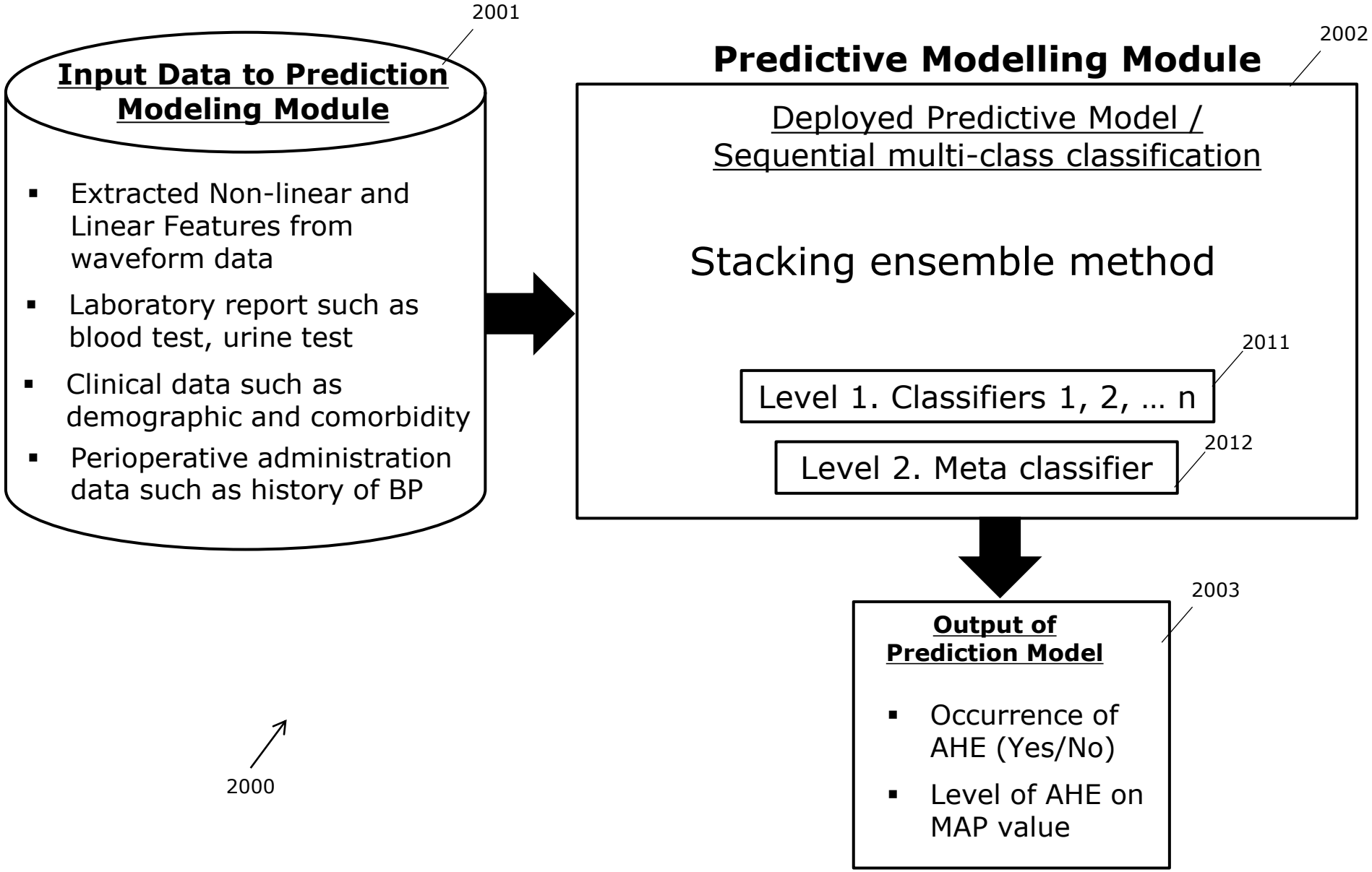

2001
Input Data to Prediction Modeling Module
Extracted Non-linear and Linear Features from waveform data
Laboratory report such as blood test, urine test
Clinical data such as demographic and comorbidity
Perioperative administration data such as history of BP
2002
Predictive Modelling Module
Deployed Predictive Model / Sequential multi-class classification
Stacking ensemble method
2011
Level 1. Classifiers 1, 2, … n
2012
Level 2. Meta classifier
2003
Output of Prediction Model
Occurrence of AHE (Yes/No)
Level of AHE on MAP value
2000

Figure 20

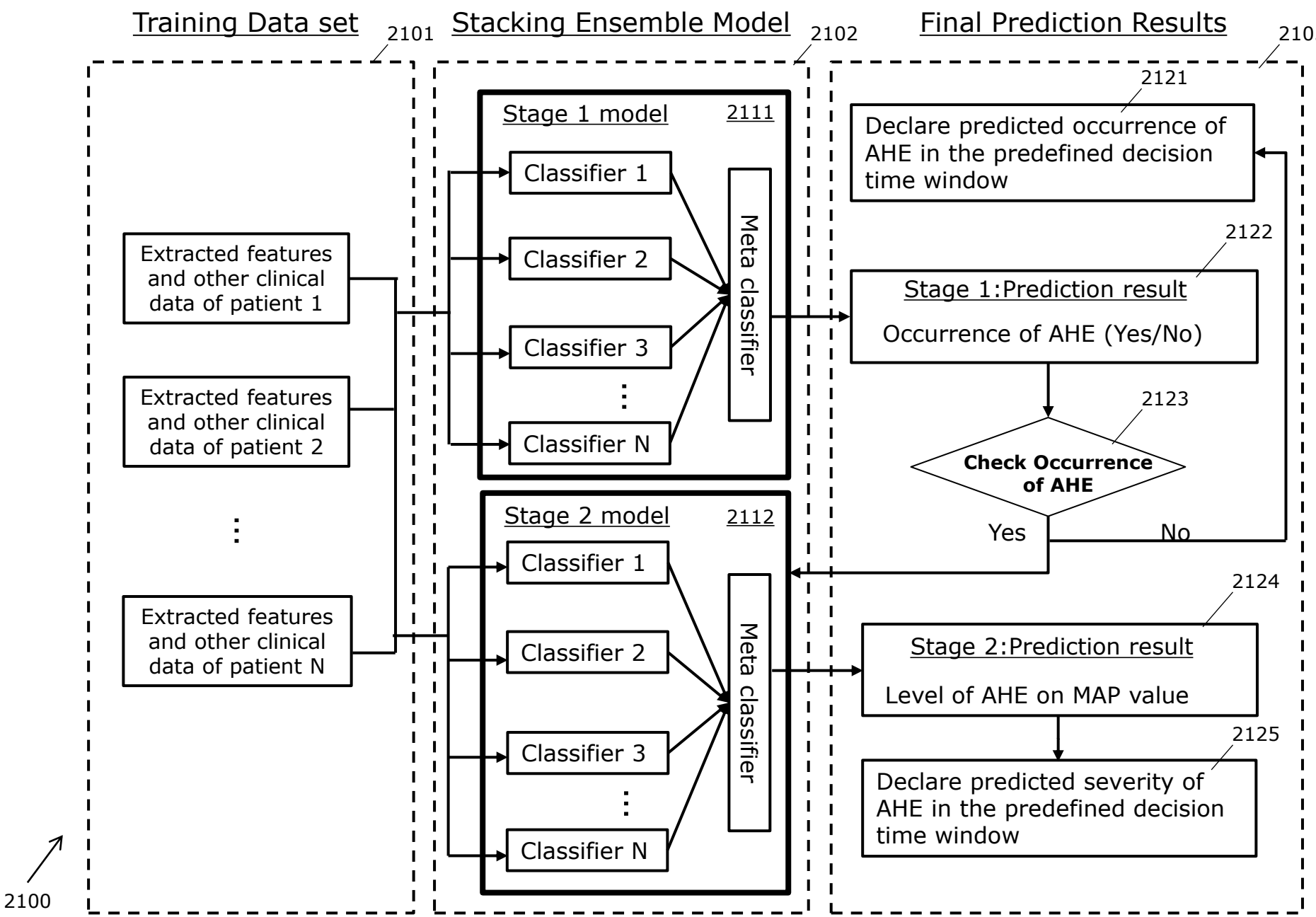

Training Data set
2101
Stacking Ensemble Model
2102
Final Prediction Results
2103
Stage 1 model
2111
Classifier 1
Classifier 2
Classifier 3
Classifier N
Meta classifier
Stage 2 model
2112
Classifier 1
Classifier 2
Classifier 3
Classifier N
Meta classifier
Extracted features and other clinical data of patient 1
Extracted features and other clinical data of patient 2
Extracted features and other clinical data of patient N
2121
Declare predicted occurrence of AHE in the predefined decision time window
2122
Stage 1:Prediction result
Occurrence of AHE (Yes/No)
2123
Check Occurrence of AHE
Yes
No
2124
Stage 2:Prediction result
Level of AHE on MAP value
2125
Declare predicted severity of AHE in the predefined decision time window
2100

Figure 21

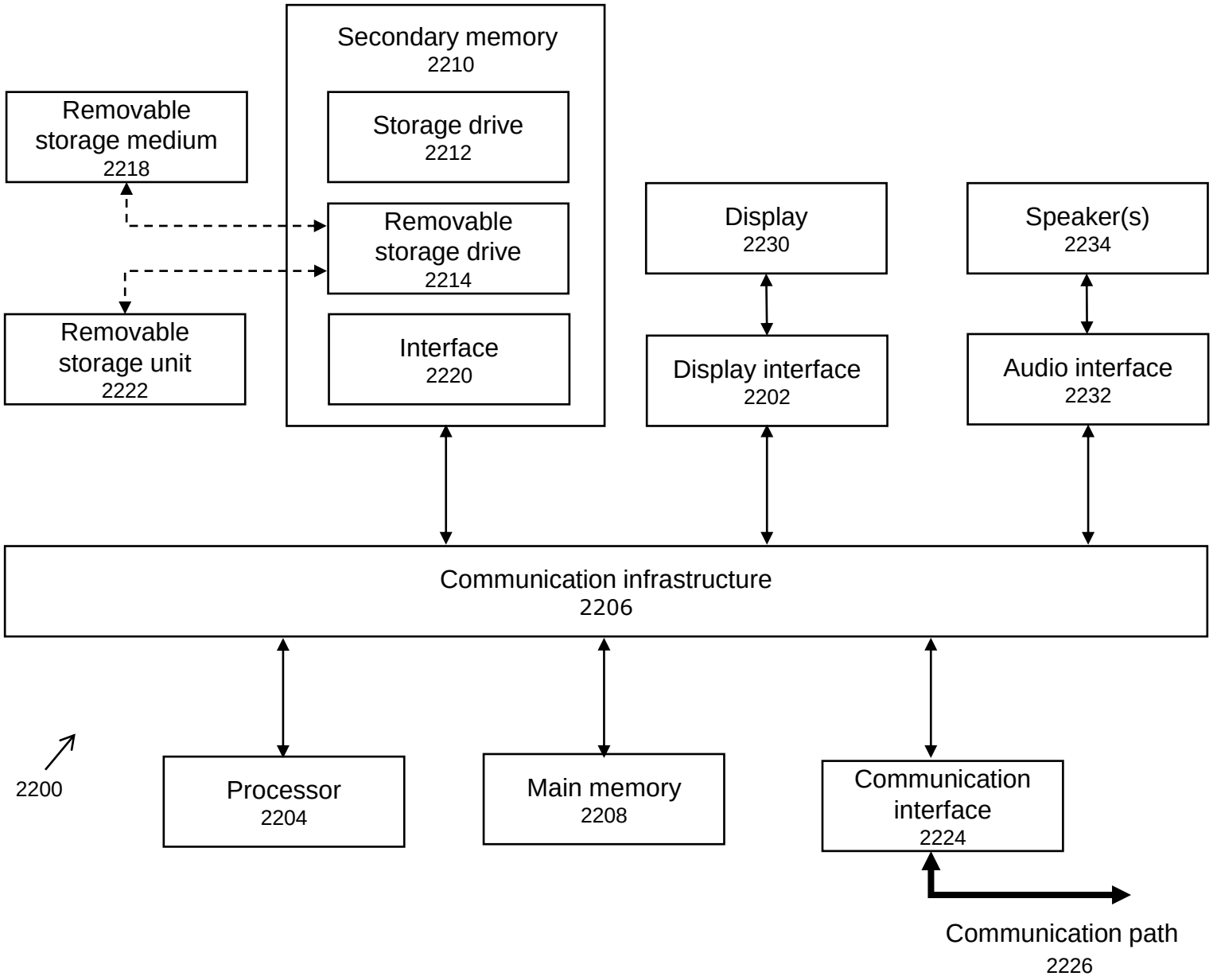

Secondary memory
2210
Removable storage medium
2218
Storage drive
2212
Removable storage drive
2214
Removable storage unit
2222
Interface
2220
Display
2230
Speaker(s)
2234
Display interface
2202
Audio interface
2232
Communication infrastructure
2206
2200
Processor
2204
Main memory
2208
Communication interface
2224
Communication path
2226

Figure 22