Cuff-Less Blood Pressure Monitoring Technologies

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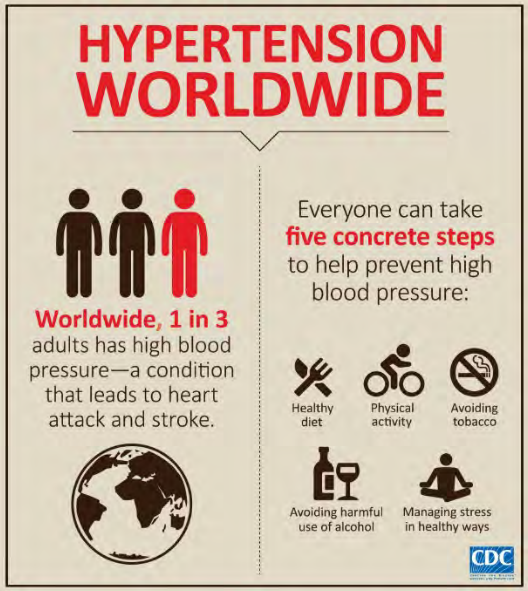
Blood Pressure (BP) Monitoring



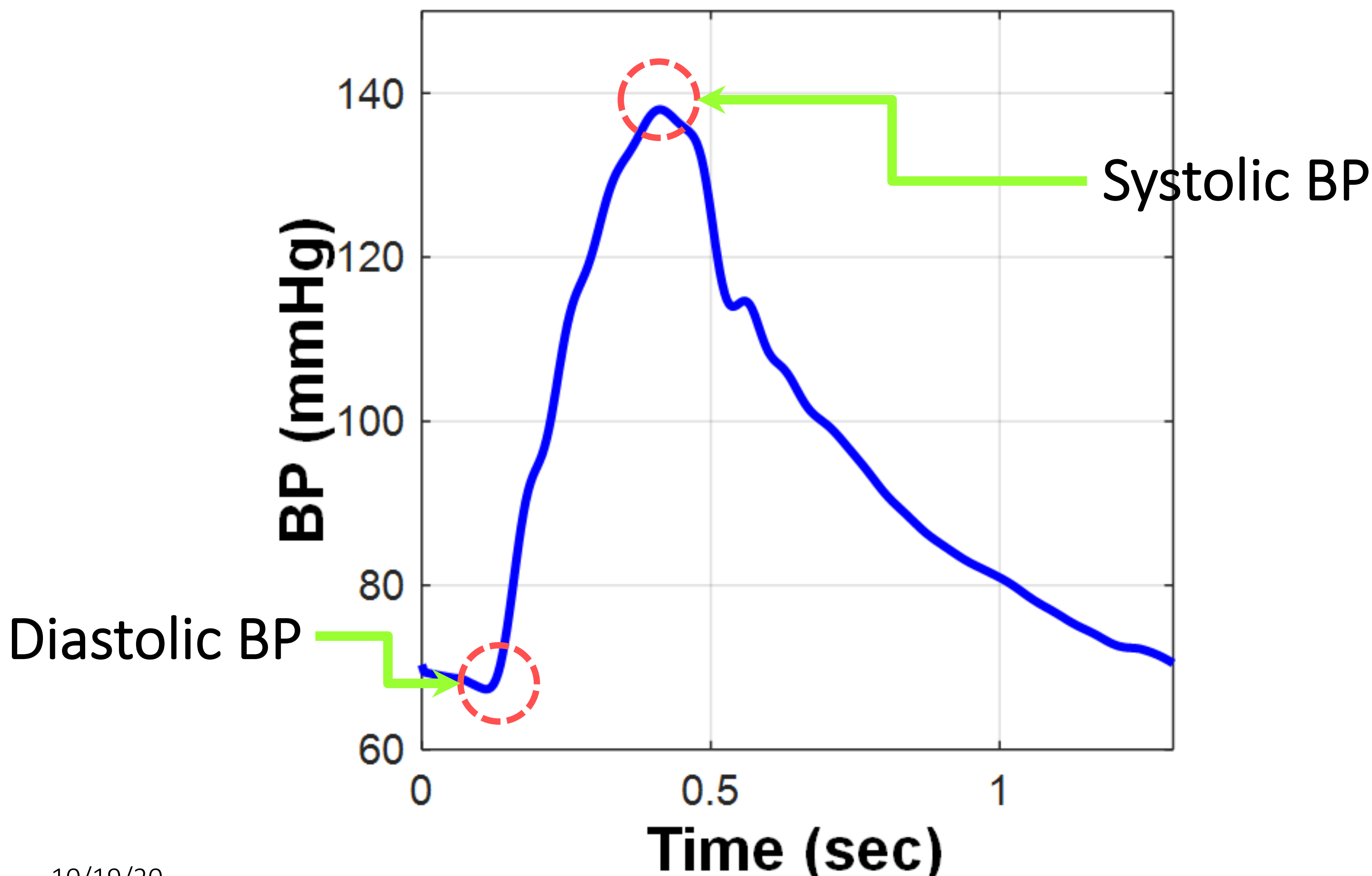
https://www.cdc.gov

- Hypertension
  1) The most prevalent chronic disease in US and globally
  2) 25% in the world's adult population
  3) Major risk factor for stroke and heart disease

- Hypertension can be treated w/ life style changes and medications;
  But, detection of hypertension is frequently missed
  1) 20% of hypertensives in US don't know they have hypertension
  2) BP in known hypertensives is often uncontrolled (50%)

→ Development of more accurate, ultra-convenient, and high-throughput BP monitoring technologies will drastically advance hypertension management and control!

Blood Pressure: Systolic & Diastolic

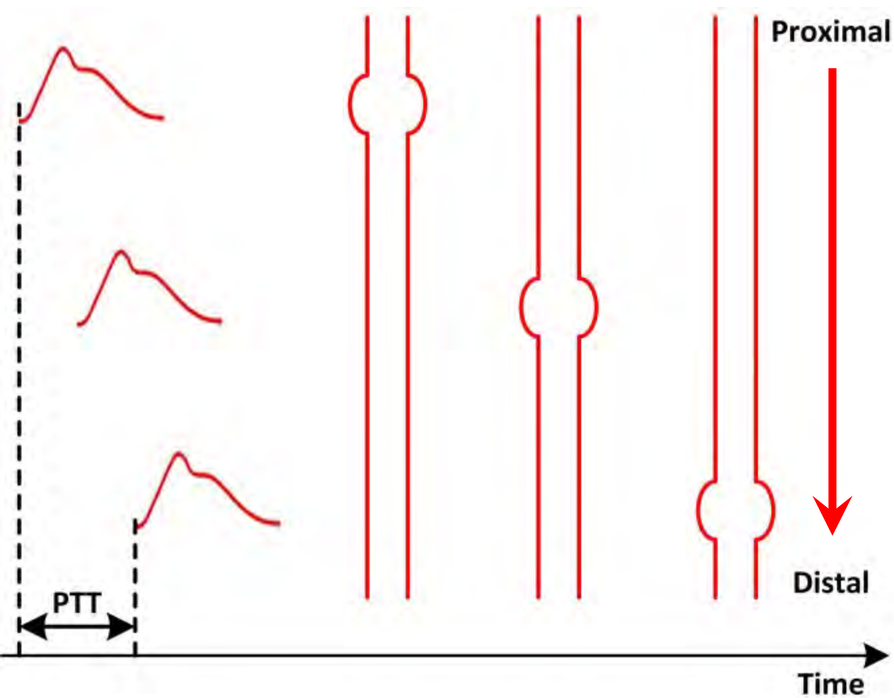


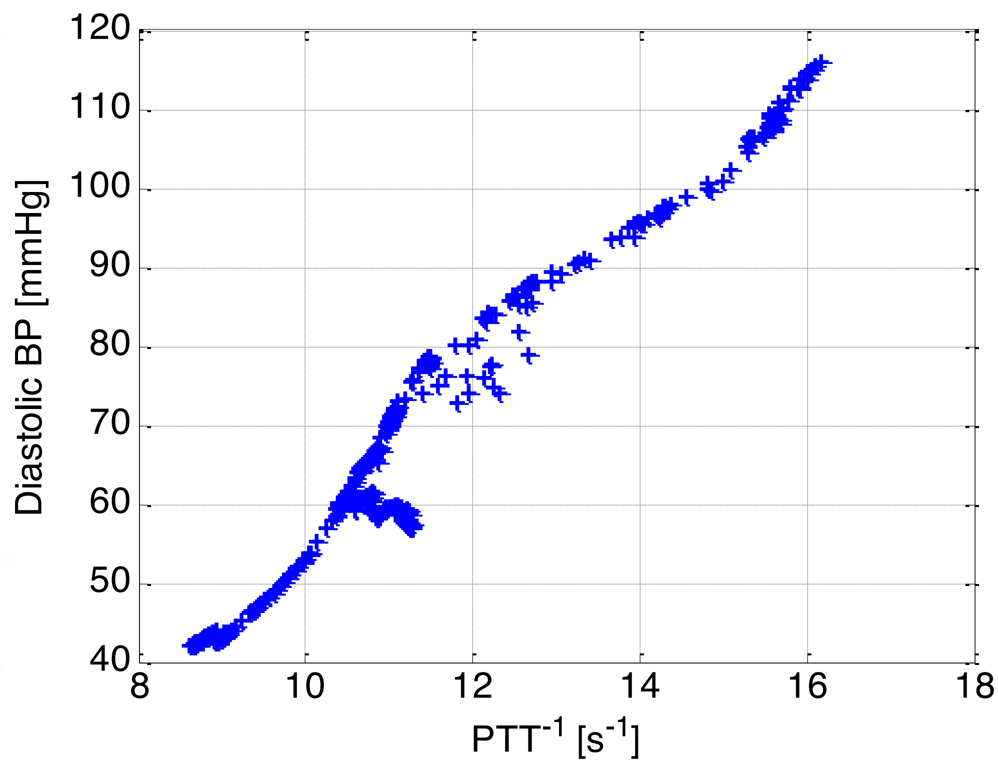
Blood Pressure Monitoring: Cuff-Based Devices

https://www.withings.com/

Cuff-Less Blood Pressure (BP) Monitoring via PTT

- PTT is time required for BP wave to travel b/w two sites in the artery.
- PTT is inversely associated with BP due to (i) BP ∝ arterial elasticity and (ii) arterial elasticity ∝ PTT^{-1}.

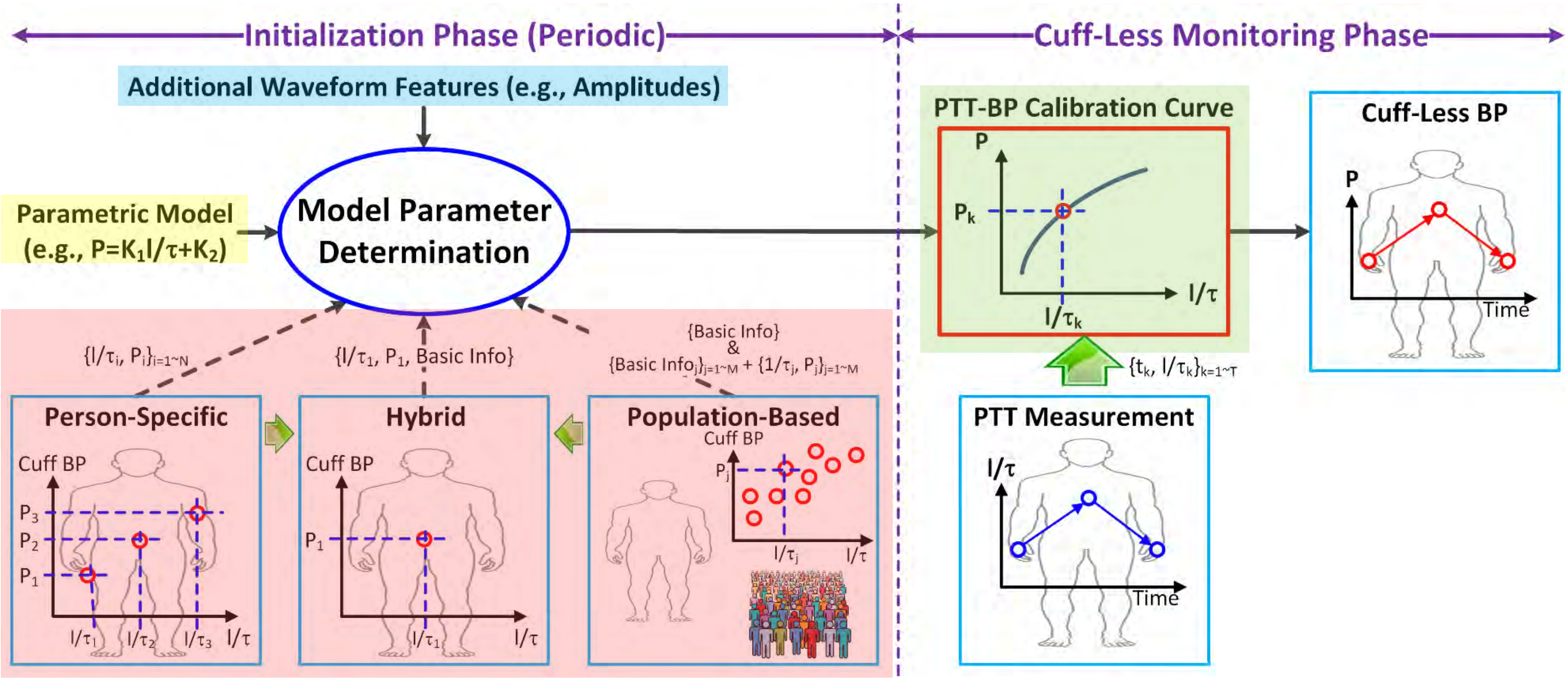




Mukkamala et al., IEEE Transactions on Biomedical Engineering (2015)

Cuff-Less Blood Pressure (BP) Monitoring via PTT

- Estimating BP from PTT requires a PTT-BP calibration curve [ms → mmHg].
  1) Parametric model relating PTT to BP
  2) Model parameter determination methods



PTT-BP Calibration/Initialization

- Calibration/Initialization: PTT [ms] → BP [mmHg]

$$P = K_1 \frac{l}{\tau} + K_2$$

  - K_1 and K_2 vary from person to person; change over time in a person; is even unknown for a given person → must be determined w/ BP-PTT measurements
  - Challenge arises from 2 unknowns to determine (K_1 and K_2)

- Calibration/Initialization Procedure
  1) To define a parametric model
  2) To determine model parameters via simultaneous cuff BP-PTT measurements (requiring a proximal and a distal arterial waveforms)
  3) To periodically repeat initialization/calibration to account for changes in the calibration parameters (e.g., due to cardiovascular aging)

PTT-BP Parametric Models: Theoretical

- Physiological Mechanisms underlying PTT –BP Relationship
  1) PTT decreases w/ increasing arterial elasticity due to fluid dynamic properties
     : BP wave travels faster through arterial wall when it is stiffer
  2) Arterial elasticity increases w/ BP due to arterial wall material properties

Bramwell-Hill Equation	Moens-Korteweg Equation
$v = \frac{l}{\tau} = \sqrt{\frac{A}{\rho}\frac{dP}{dA}}$	$v = \frac{l}{\tau} = \sqrt{\frac{A}{\rho}\frac{dP}{dA}}$ & $C = \frac{dA}{dP} = \frac{2\pi r^3}{Eh}$ ↓ $v = \frac{l}{\tau} = \sqrt{\frac{Eh}{2r\rho}}$

PTT-BP Parametric Models: Theoretical

- Physiological Mechanisms in PTT –BP Relationship
  1) PTT decreases w/ increasing arterial elasticity due to fluid dynamic properties
  2) Arterial elasticity increases w/ BP due to arterial wall material properties
     : Arterial wall gets stiffer as it expands when it is subject to higher BP

Hugh Model	Wesseling Model
$E = E_0 e^{\alpha P}$	$A(P) = A_{max}\left[\frac{1}{2} + \frac{1}{\pi}\tan^{-1}\left(\frac{P - P_0}{P_1}\right)\right]$ $C(P) = \frac{dA}{dP} = \frac{A_{max}}{\pi P_1\left[1 + \left(\frac{P - P_0}{P_1}\right)^2\right]}$

PTT-BP Parametric Models: Theoretical

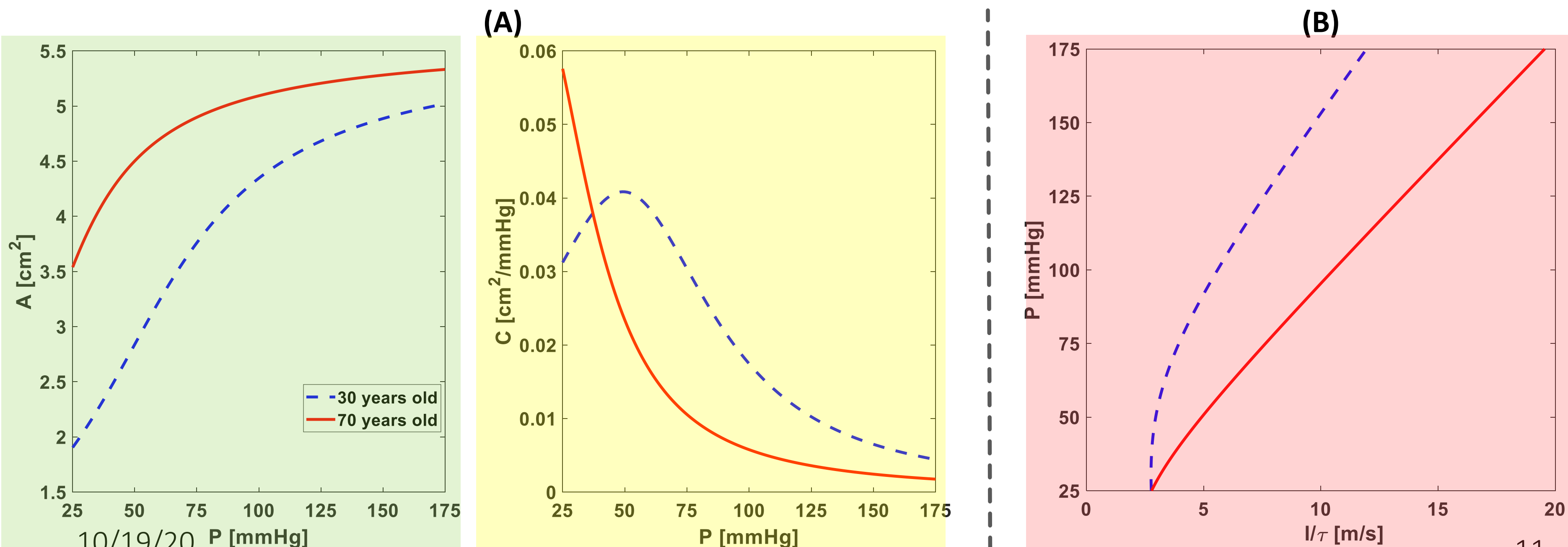
- PTT-BP Models can be derived by combining the models representing these two physiological mechanisms:

Model	Parameters	Incorporated Mechanisms
$P = K_1 \ln\left(\frac{\tau}{l}\right) + K_2$	$K_1 = -\frac{2}{\alpha}, K_2 = \frac{1}{\alpha}\ln\left(\frac{2r\rho}{E_0 h}\right)$	M-K + Hugh
$P = K_1 \frac{l}{\tau} + K_2$	$K_1 = \sqrt{\frac{2\rho P_1}{\pi + 2}}, K_2 = P_0$	B-H + Wesseling / High P
$P = K_1 \left(\frac{l}{\tau}\right)^2 + K_2$	K_1, K_1	B-H + Ma's A & C (PNAS, 2018)
$\frac{\tau}{l} = \frac{2819.7}{\sqrt{\pi P_1\left(1 + \left(\frac{P - P_0}{P_1}\right)^2\right)\left(\frac{1}{2} + \frac{1}{\pi}\tan^{-1}\left(\frac{P - P_0}{P_1}\right)\right)}}$	P_0, P_1	B-H + Wesseling

Ma et al., PNAS (2018)

PTT-BP Parametric Models: Theoretical

- PTT-BP Model: Insights (e.g., B-H + W $\frac{\tau}{l} = \frac{2819.7}{\sqrt{\pi P_1\left(1+\left(\frac{P-P_0}{P_1}\right)^2\right)\left(\frac{1}{2}+\frac{1}{\pi}\tan^{-1}\left(\frac{P-P_0}{P_1}\right)\right)}}$)
  1) (A) With aging, arterial cross-sectional area (A) becomes less dependent upon BP while arterial compliance (C) becomes more dependent upon BP
  2) (B) The shape of the PTT-BP relationship may be age-dependent and becomes nearly a line relationship in PWV in the elderly



PTT-BP Parametric Models: Empirical

- To achieve adequate fitting of PTT-BP data, w/o reference to physiological mechanisms

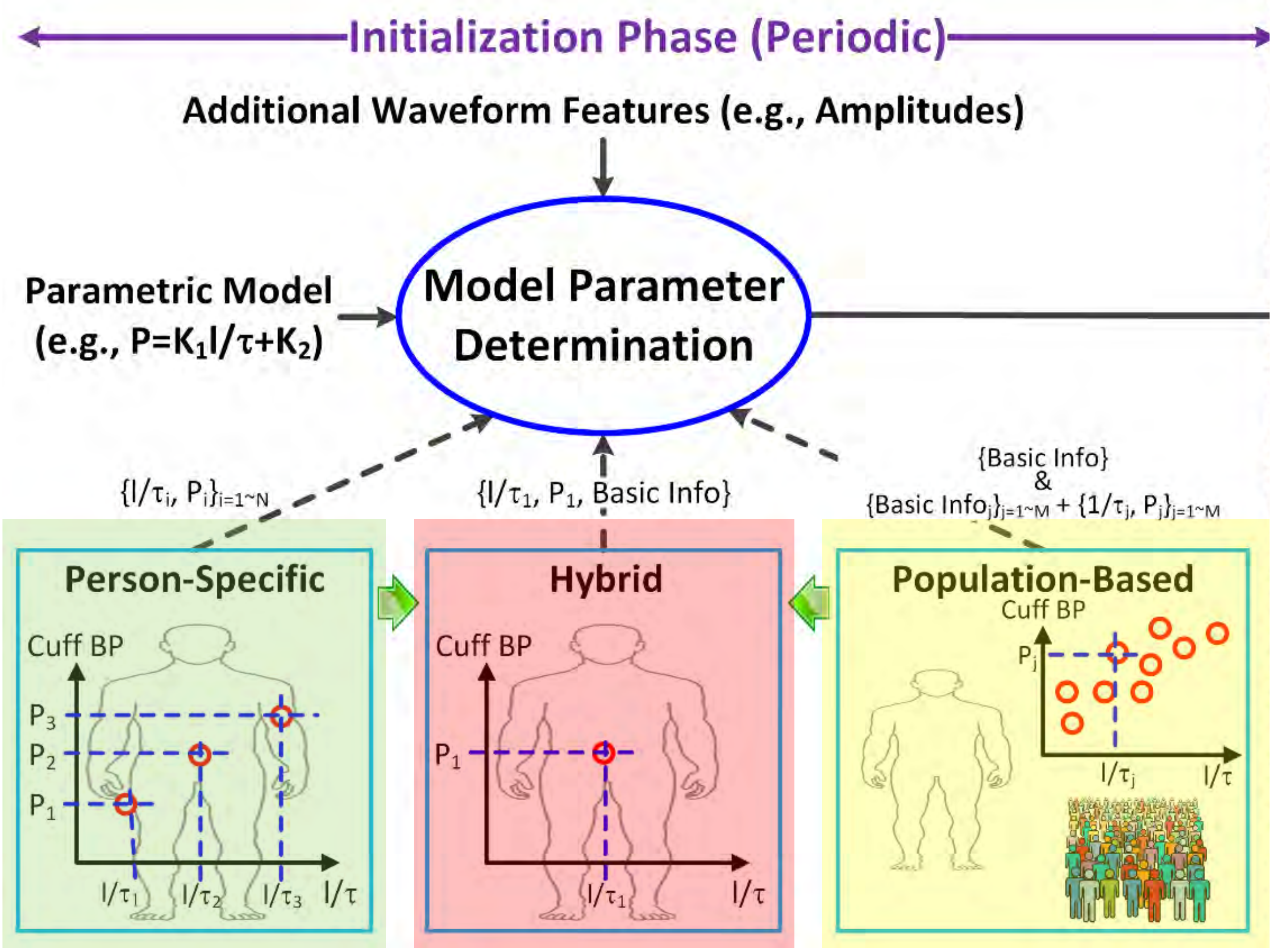
Linear Models	$P = K_1 \frac{\tau}{l} + K_2$
Nonlinear Models ($x = \frac{\tau}{l}$ or $\frac{l}{\tau}$)	$P = K_1 x^2 + K_2 x + K_3$ $P = K_1 x^p + K_2$ $P = K_1 e^{K_2 x}$
PP Models[1]	$PP = K \left(\frac{l}{\tau}\right)^2$
Models w/o Non-Physiological BP[2]	$P = \frac{K_1}{\left(\frac{\tau}{l} - K_2\right)^2} + K_3$

[1]: The model may not hold in general, as K depends on the difference in the arterial cross-sectional areas at systole and diastole and may thus vary considerably within a person; integrating the B-H equation yields $PP = \rho \left(\frac{l}{\tau}\right)^2 \ln\left(\frac{A_s}{A_d}\right) \approx \rho \left(\frac{l}{\tau}\right)^2 \left(\frac{A_s - A_d}{A_d}\right)$.

[2]: The model may be practical for initialization, but is still not physiological; physiologically correct limiting behavior is for PTT to be finite at zero BP and approach zero as BP approaches infinity.

Cuff-Less Blood Pressure (BP) Monitoring via PTT

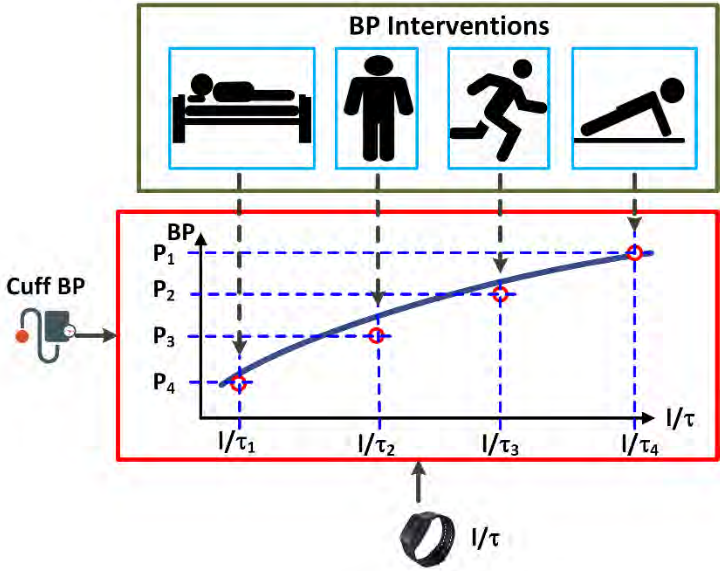
- How can the parameters in PTT-BP parametric model be determined?



Model Parameter Determination

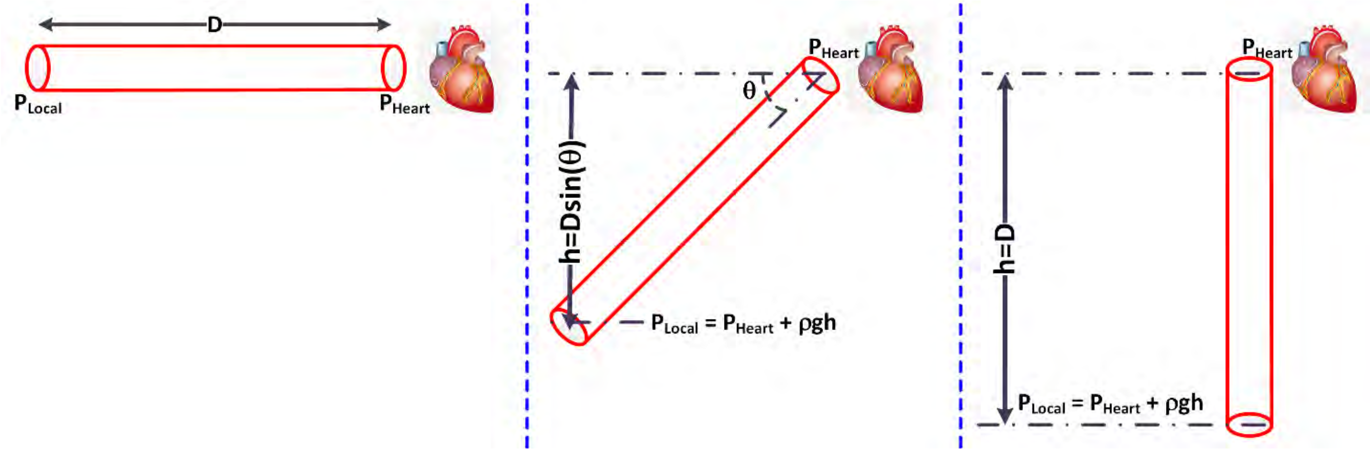
- Person-Specific Method: A person-specific method intends to determine all the model parameters in the calibration model. It involves measuring cuff BP and PTT during multiple interventions that perturb BP in the person.
  1) Employ one or more interventions to perturb BP in the person
  2) Measure cuff BP and PTT during the baseline period and each intervention
  3) Fit the model to the multiple PTT-BP data pairs to determine all parameters

Intervention	BP Effect [mmHg]	Convenience Level
Slow Breathing	<|5|/<|5|	High
Supine to Standing	<|10|/+4	High
Cold Pressor	+16/+14	Low
Exercise	+40/+40 to -9/-4 (1-hr later)	Moderate (could be incorporated in daily life)
Sustained Handgrip	+45-50/+40	Low
Mental Arithmetic	+20/+11	Low (requires person adherence)
Valsalva Maneuver	-15/-15	Low (requires special cuff to detect fast change)
Hydrostatic Maneuver Hand Lowering/Raising Supine to Seated	-50/-50 to +50/+50 +30/+30	High (but requires heart level detection)



Model Parameter Determination

- Person-Specific Method: Hydrostatic Maneuver
  1) High convenience + large BP change
  2) Use of the weight of blood column: ~7 mmHg for 10 cm height change



- Local wrist/hand PTT: ~50 mmHg BP change
- PAT: ~25 mmHg (effective BP measurement site may be ~ midpoint of the arm)
- C-F PTT: ~30 mmHg w/ supine to standing (effective BP measurement site may be ~ abdomen)

Model Parameter Determination

- Person-Specific PTT-BP Calibration: Other Considerations
  1) Leveraging natural BP variations that occur over time in a person due to stress, physical activity, meals, and other factors: ~5 mmHg DP / ~6-9 mmHg SP [BP change is small and timing is unknown]

  2) Different BP interventions change BP via different physiological mechanisms → Employing a multitude of interventions that invoke an array of physiological mechanisms may provide a good balance for more effective calibration

  3) SP or DP? One PTT may be used to calibrate both DP and SP, b/c usually there is modest correlation b/w DP and SP:

$$P_s = G_1 P_d + G_2$$

w/ G_1 and G_2 functions of age and gender.

Yet, models relating one time delay to SP and DP will obviously break down when the two BP values diverge!

Model Parameter Determination

- Population-Based Method: A population-based method determines all the model parameters in the calibration model w/o using any BP-perturbing interventions. It involves making the model parameters functions of basic information of the person (e.g., age and gender) using a training dataset comprising cuff BP and PTT measurements from a cohort of subjects.

Example: B-H equation + Wesseling model

$$\frac{\tau}{l} = \frac{2819.7}{\sqrt{\pi P_1 \left(1 + \left(\frac{P - P_0}{P_1}\right)^2\right)\left(\frac{1}{2} + \frac{1}{\pi}\tan^{-1}\left(\frac{P - P_0}{P_1}\right)\right)}}$$

w/ $P_0 = 72 - 0.89\text{age}$ (F) / $P_0 = 76 - 0.89\text{age}$ (M), $P_1 = 57 - 0.44\text{age}$

Model Parameter Determination

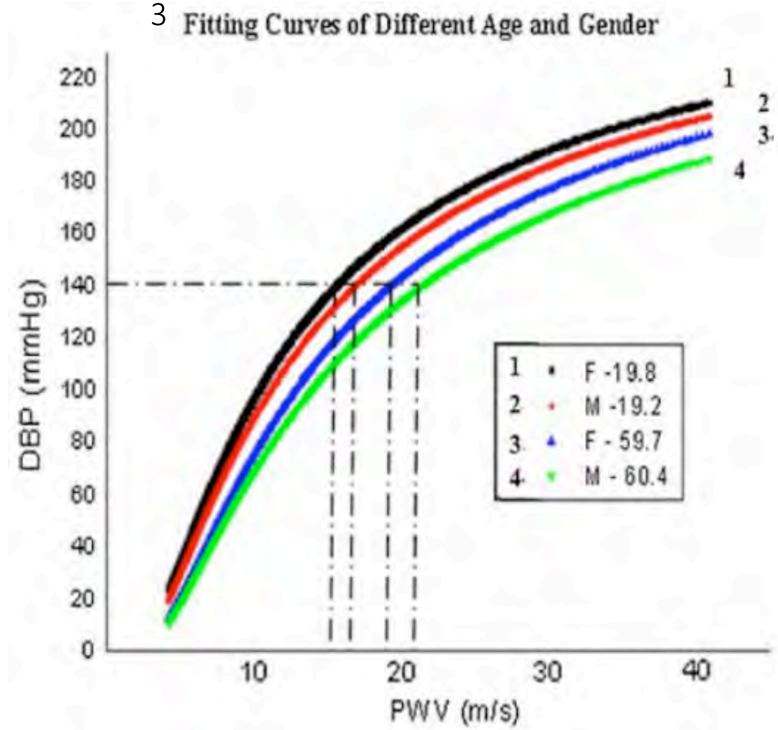
- Population-Based Method: Examples

$$\frac{l}{\tau} = (0.00131\text{age} - 0.0168)P_d + 3.35$$ [1]

(r^2=0.71)

$$P_d = (22 \pm 14)\frac{l}{\tau} + K_2$$ [2]

3



- The efficacy of the models remains controversial

[1]Carroll, J. D., Shroff, S., Wirth, P., Halsted, M. & Rajfer, S. Arterial Mechanical Properties in Dilated Cardiomyopathy. J. Clin. Invest. 87, 1002–1009 (1991).

[2]Butlin, M., Shirbani, F., Barin, E., Tan, I., Spronck, B. & Avolio, A. P. Cuffless Estimation of Blood Pressure: Importance of Variability in Blood Pressure Dependence of Arterial Stiffness across Individuals and Measurement Sites. IEEE Trans. Biomed. Eng. 65, 2377–2383 (2018).

[3]Chen, Y., Wen, C., Tao, G., Bi, M. & Li, G. Continuous and Noninvasive Blood Pressure Measurement: A Novel Modeling Methodology of the Relationship between Blood Pressure and Pulse Wave Velocity. Ann. Biomed. Eng. 37, 2222–2233 (2009).

Model Parameter Determination

- Hybrid Method: A hybrid method involves measuring cuff BP and PTT in the person to determine a single model parameter and using the person's basic information and a training dataset to determine the remaining parameters.
  1) PAT to Mean BP, $P = K_1 \ln\left(\frac{\tau}{l}\right) + K_2$, $K_1 = -64.5$ mmHg, K_2 determined w/ baseline PAT-cuff BP measurement (healthy subjects)[1]
  2) PAT to Mean BP, $P = K_1 \ln\left(\frac{\tau}{l}\right) + K_2$, $K_1 = -22.2$ mmHg, K_2 determined w/ baseline PAT-cuff BP measurement (old hypertensive subjects)[2]
  3) PAT to SP, 5-parameter model, 4 parameters determined w/ training dataset, intercept determined w/ baseline PAT-cuff BP measurement[3]

→ Essentially a mixture of person-specific method and population-based method
Trade-off b/w accuracy and convenience

[1]Zheng, Y.-L., Yan, B. P., Zhang, Y.-T. & Poon, C. C. Y. An Armband Wearable Device for Overnight and Cuff Less Blood Pressure Measurement. IEEE Trans. Biomed. Eng. 61, 2179–2186 (2014).
[2]Zheng, Y., Poon, C. C. Y., Yan, B. P. & Lau, J. Y. W. Pulse Arrival Time Based Cuff-Less and 24-H Wearable Blood Pressure Monitoring and its Diagnostic Value in Hypertension. J. Med. Syst. 40, 195 (2016).
[3]Gesche, H., Grosskurth, D., Küchler, G. & Patzak, A. Continuous Blood Pressure Measurement by using the Pulse Transit Time: Comparison to a Cuff-Based Method. Eur. J. Appl. Physiol. 112, 309–315 (2012).

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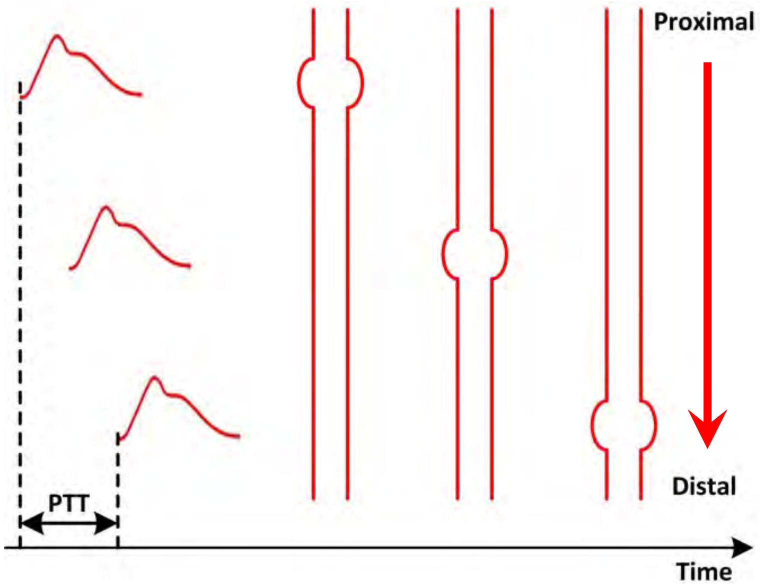
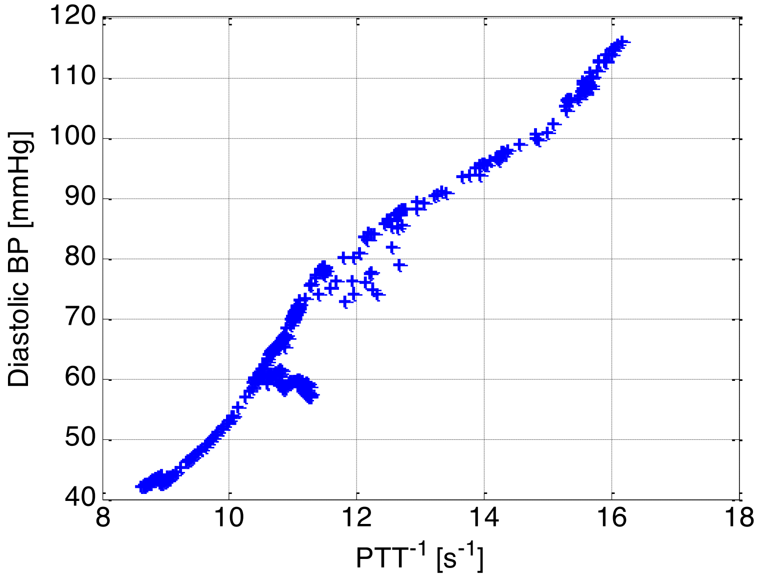
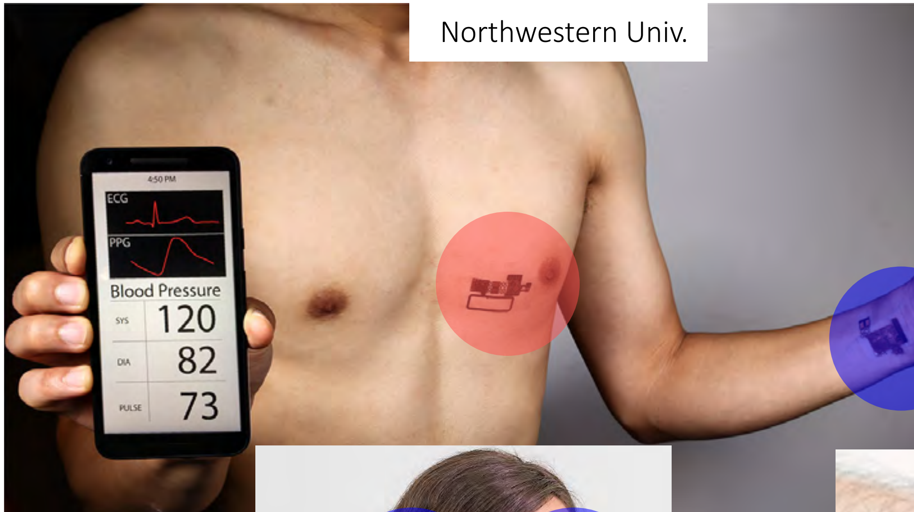




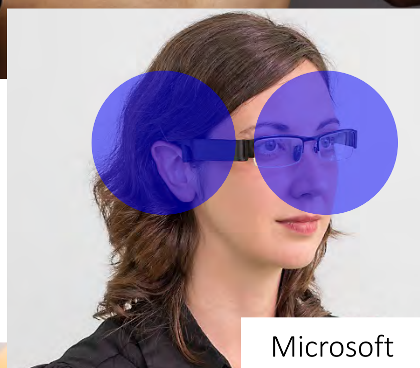
- In practice, PTT principle is inappropriately used in cuff-less BP monitoring for the sake of convenience
  1) ECG as proximal timing reference → inaccuracy due to pre-ejection period
  2) Finger pulse as distal timing reference → inaccuracy due to smooth muscles

Mukkamala et al., IEEE Transactions on Biomedical Engineering (2015)



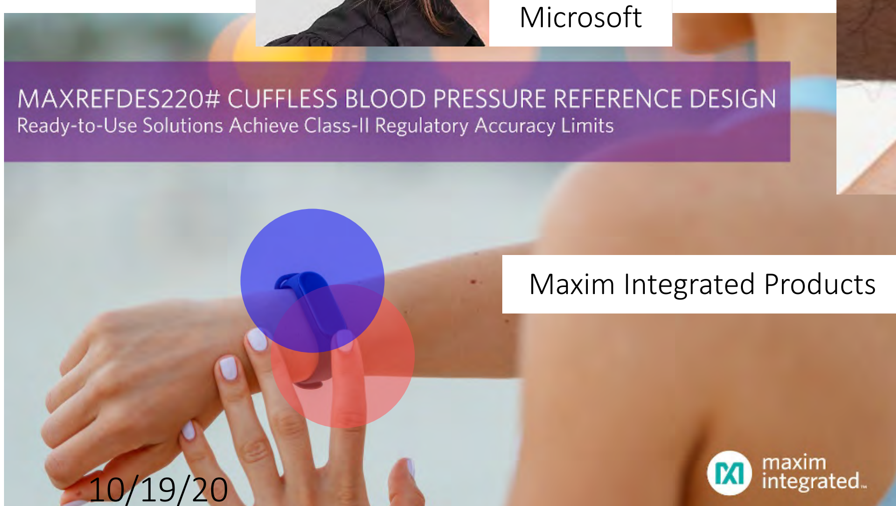
Northwestern Univ.

Maisense



Microsoft

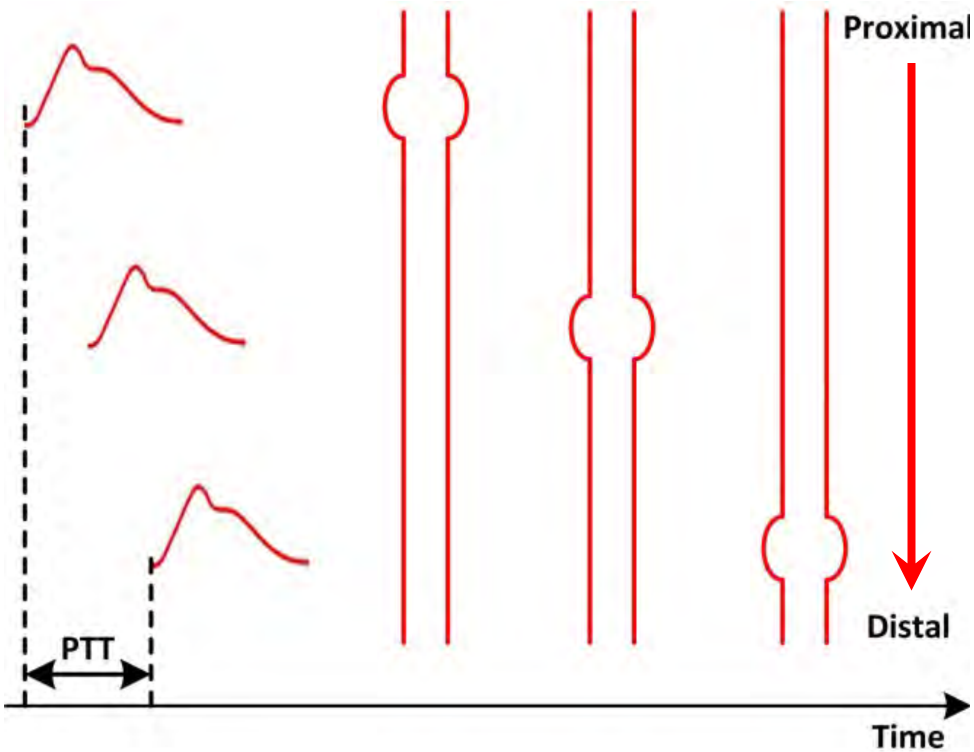
Heartisans

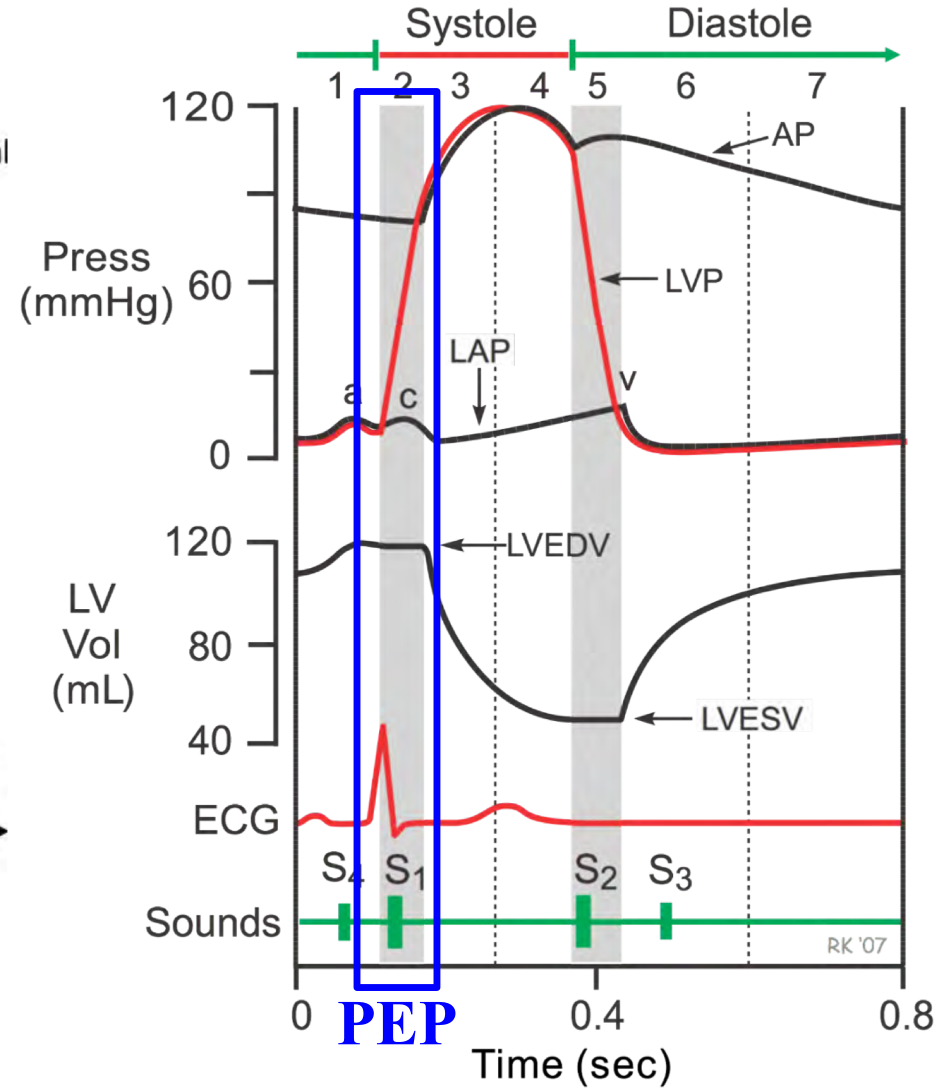


Maxim Integrated Products

Omron

Pre-Ejection Period (PEP) as Disturbance





https://www.cvphysiology.com/

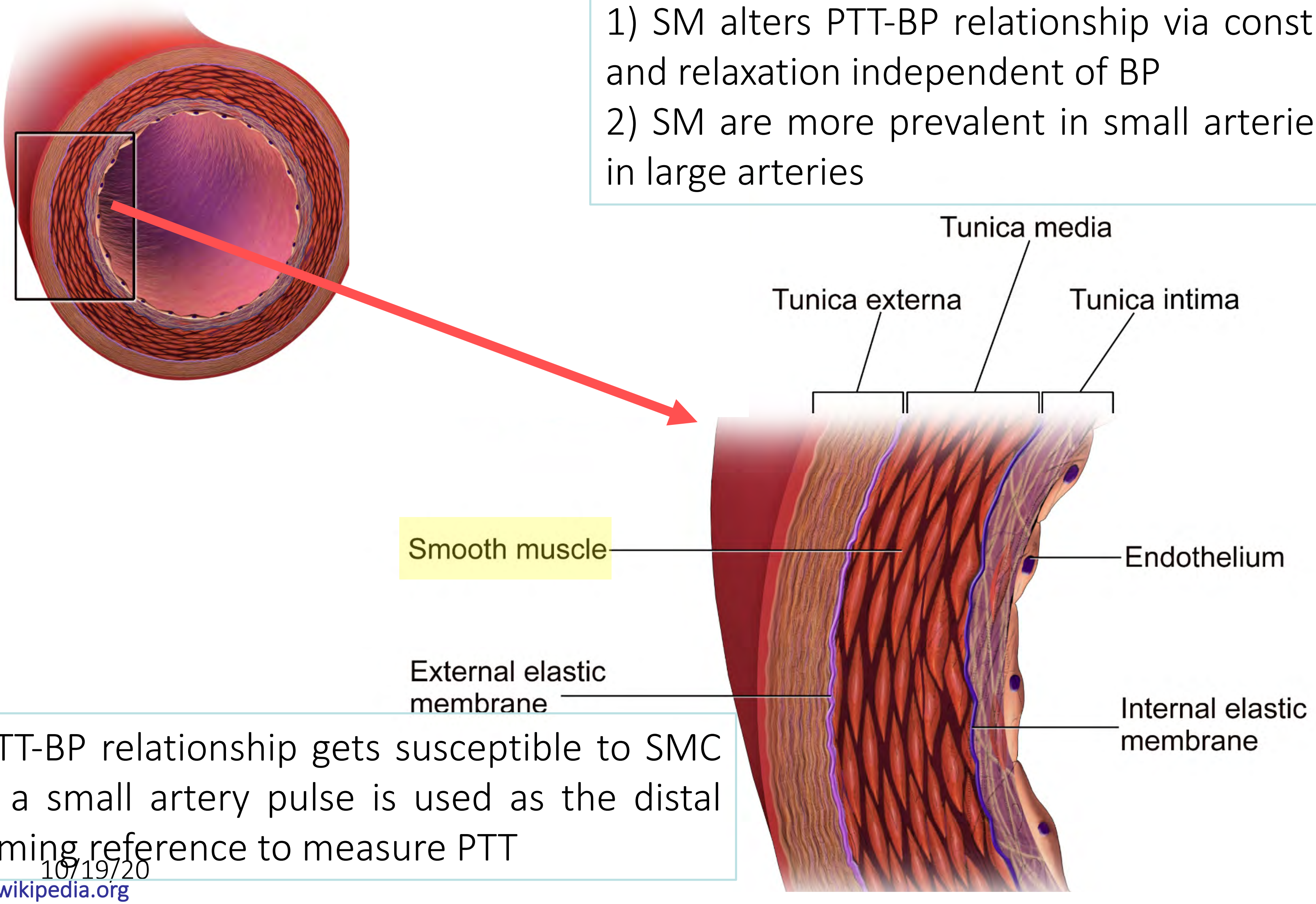
1) ECG as proximal timing reference

→ Inaccuracy due to PEP

Mukkamala et al., IEEE Transactions on Biomedical Engineering (2015)

Smooth Muscle (SM) as Disturbance

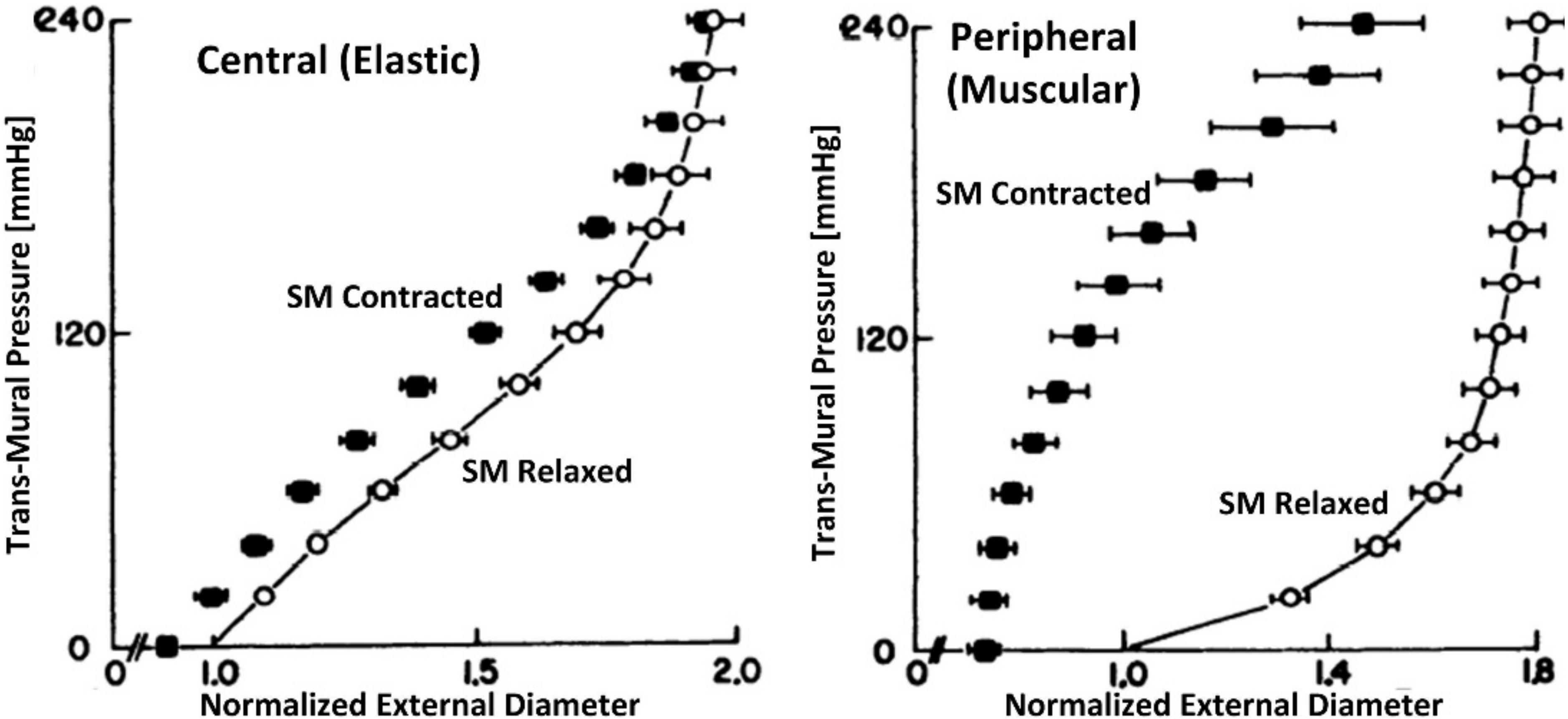
1) SM alters PTT-BP relationship via constriction and relaxation independent of BP
2) SM are more prevalent in small arteries than in large arteries



PTT-BP relationship gets susceptible to SMC if a small artery pulse is used as the distal timing reference to measure PTT

en.wikipedia.org

Smooth Muscle Contraction as Disturbance



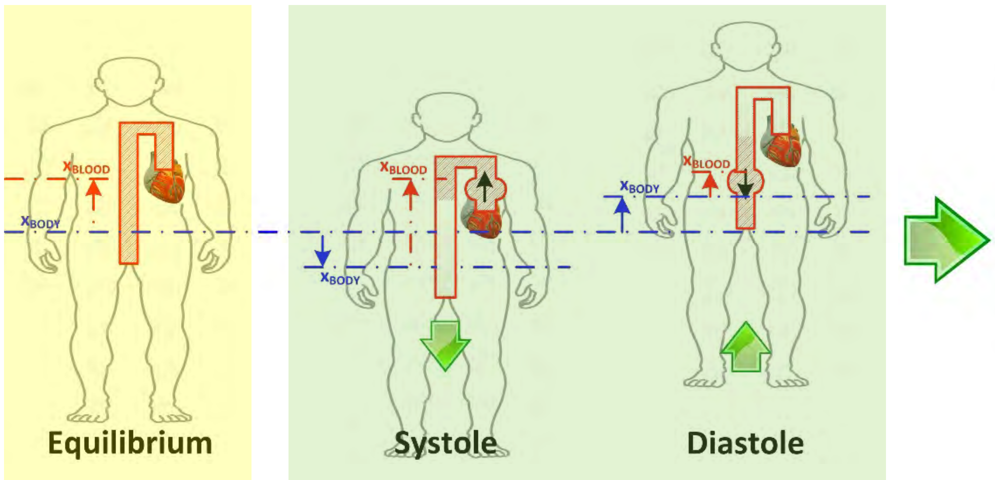
Cox, American Journal of Physiology (1978)

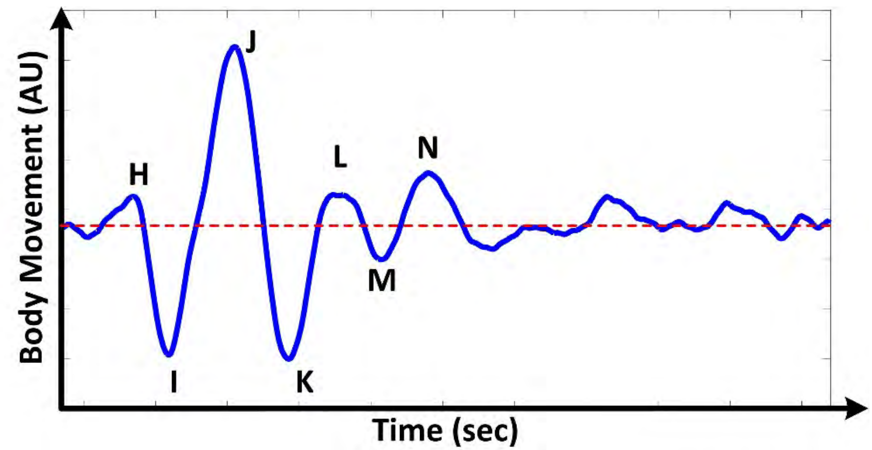
2) Finger pulse as distal timing reference → Inaccuracy due to smooth muscles

Mukkamala et al., IEEE Transactions on Biomedical Engineering (2015)

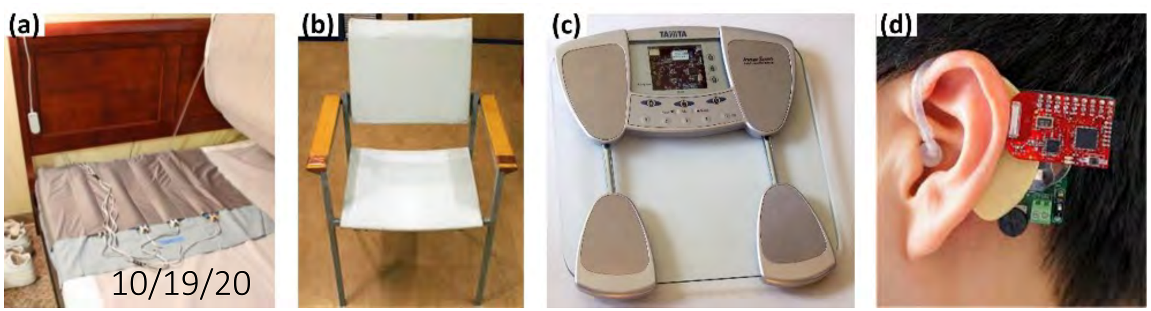
Ultra-Convenient Cuff-Less BP Monitoring via BCG

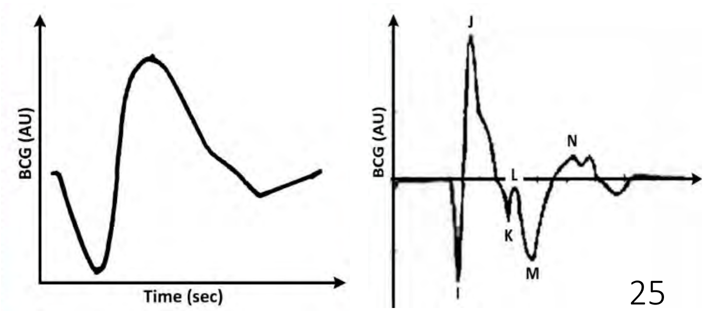
- Ballistocardiogram (BCG): Heartbeat-Induced Body Movement
  - For ~150 years, it has been known that heartbeat induces body movement





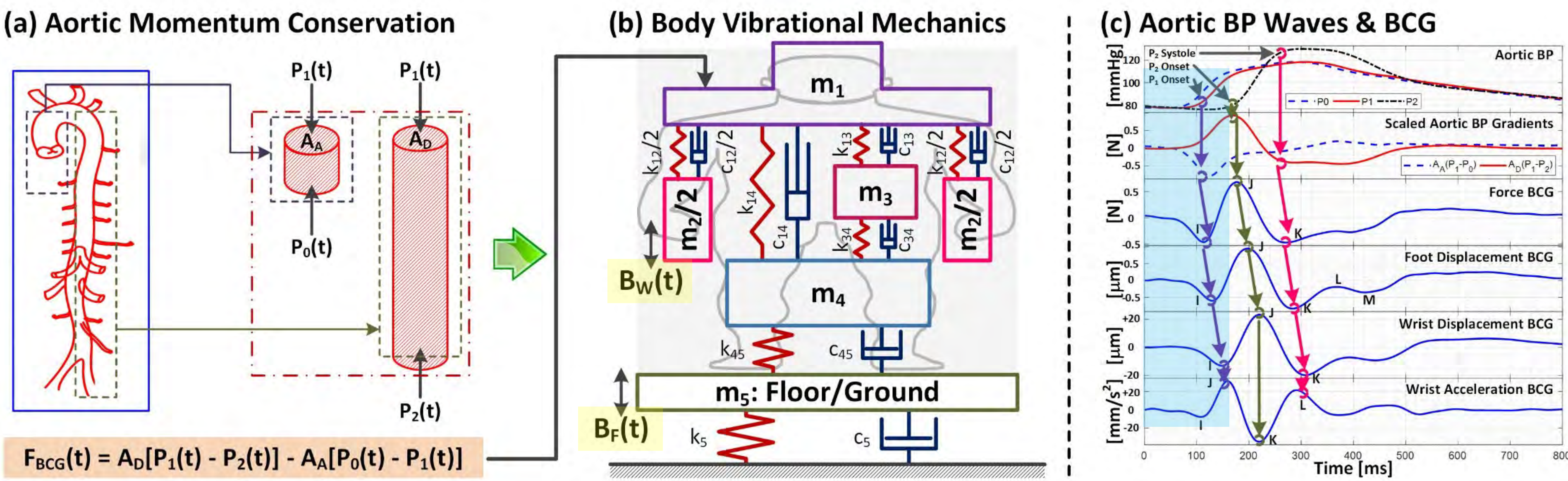
  - BCG is amenable to ultra-convenient instrumentation
  - Mechanism underlying the BCG waves has remained mysterious





BCG: Elucidating Physiological Mechanism

- Physiological mechanism underlying the genesis of the BCG is elucidated, for the first time, by developing a simple lumped-parameter model
  1) BCG $F_{BCG}(t)$ originates from ascending & descending aortic BP gradients
  2) The limb BCG signals are the responses of compliant body to the BCG
  3) BCG waves (+/- peaks) elucidate timing/amplitude characteristics in BP waves



Kim et al., Scientific Reports (2016) / Yousefian et al., Scientific Reports (2019a)

BCG: Physiological Interpretation & Insights

- The BCG waveform elucidates timing/amplitude info on aortic BP waves
- The BCG waveform exhibits meaningful changes in response to BP changes

Relationship b/w BCG and Timing/Amplitude Characteristics of Aortic BP Waves

Arterial BP	Arterial BP Gradients	Foot Displacement BCG	Wrist Acceleration BCG
Aortic Inlet BP (P_1) Onset	Peak, P_0-P_1	I	J
Aortic Outlet BP (P_2) Onset	Peak, P_1-P_2	J	K
Aortic Outlet BP (P_2) Systole	Valley, P_1-P_2	K	L
Aortic Inlet BP (P_1) Amplitude	Positive Amplitude, P_1-P_2	J Amplitude	K Amplitude
Aortic Outlet BP (P_2) Amplitude	Peak-Peak Amplitude, P_1-P_2	J-K Amplitude	K-L Amplitude

Kim et al., Scientific Reports (2016) / Yousefian et al., Scientific Reports (2019)

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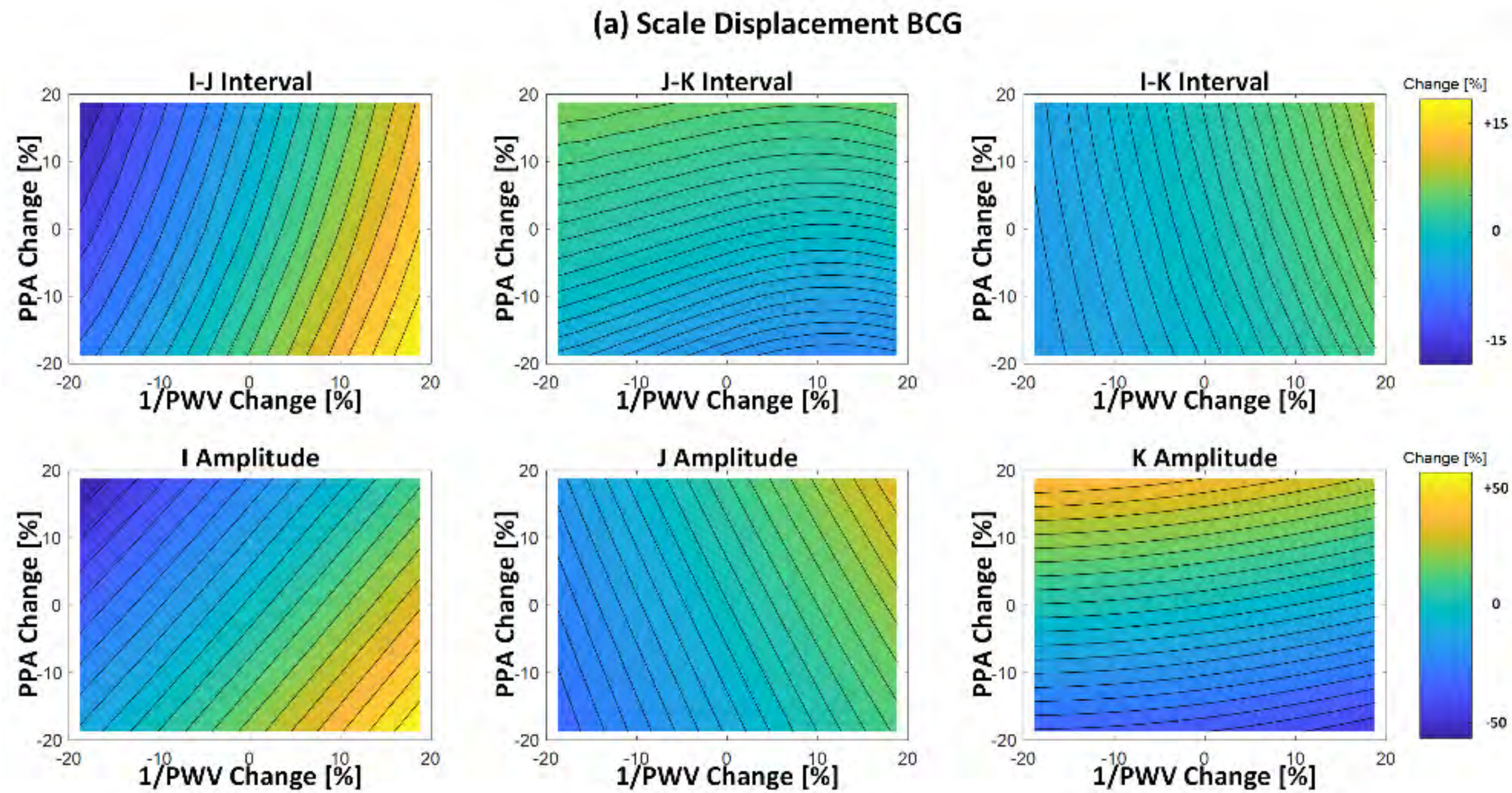

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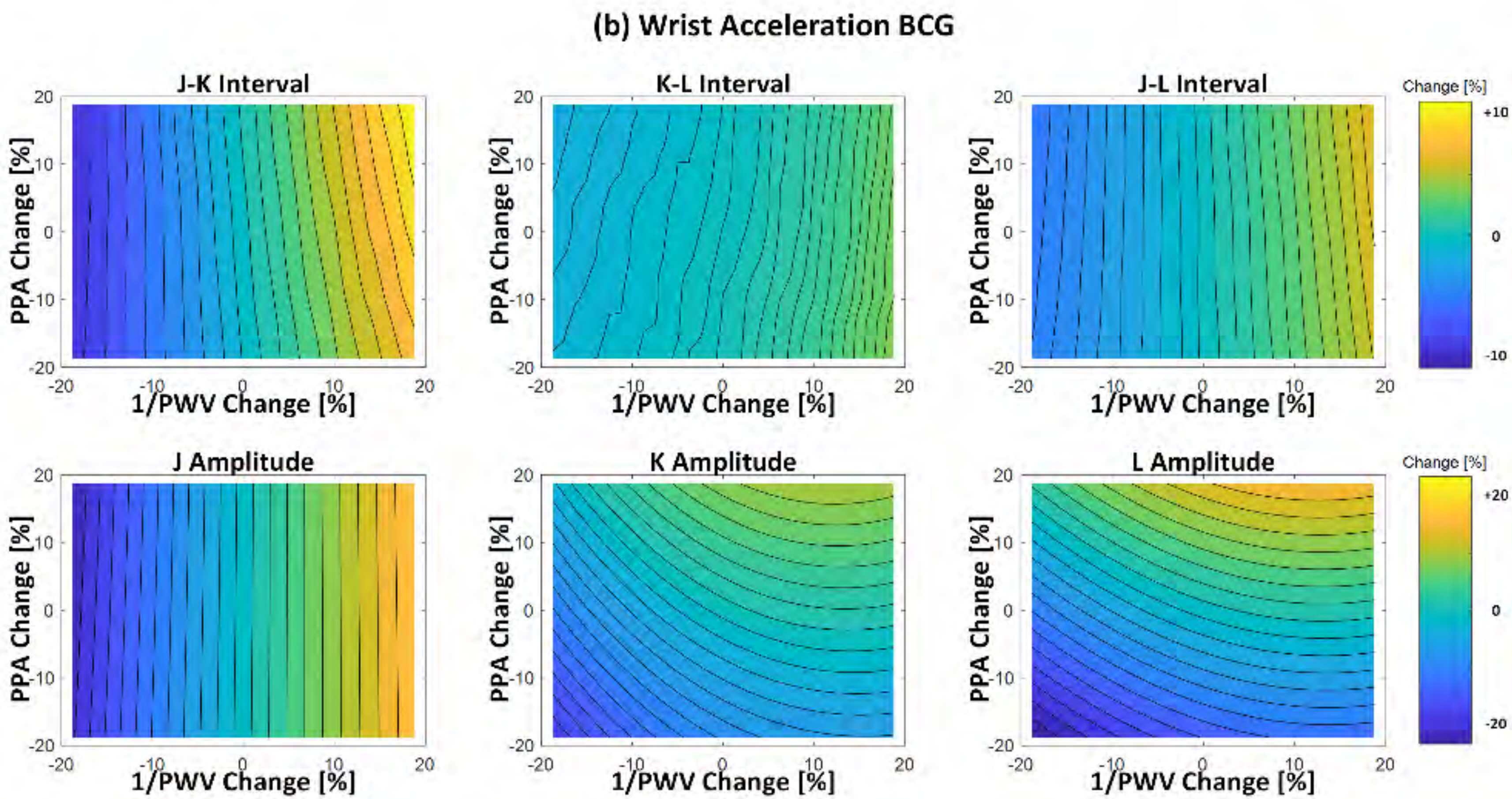
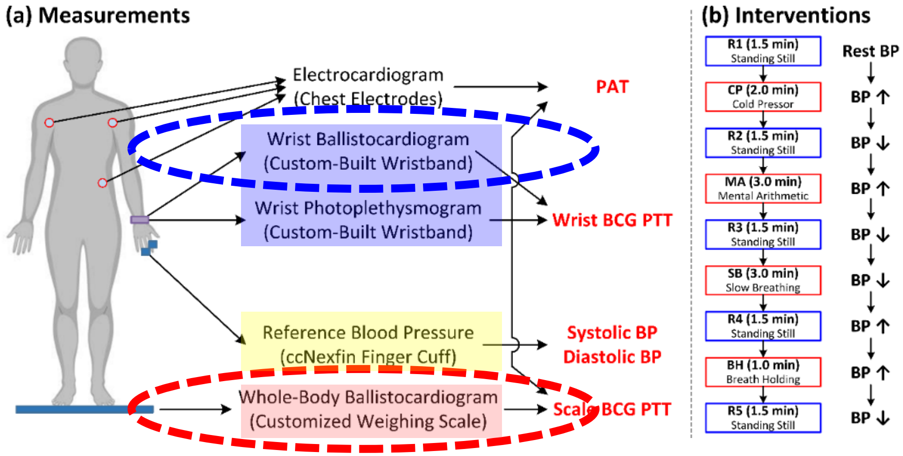
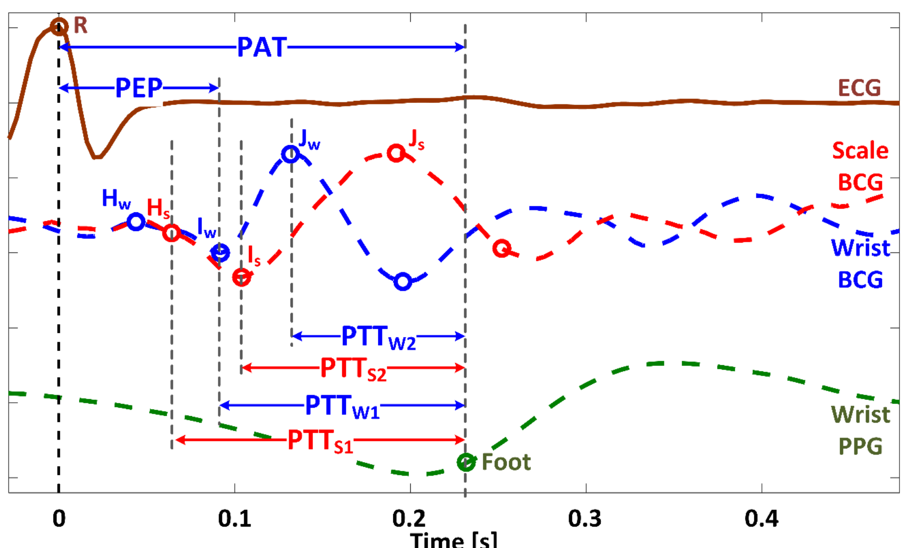


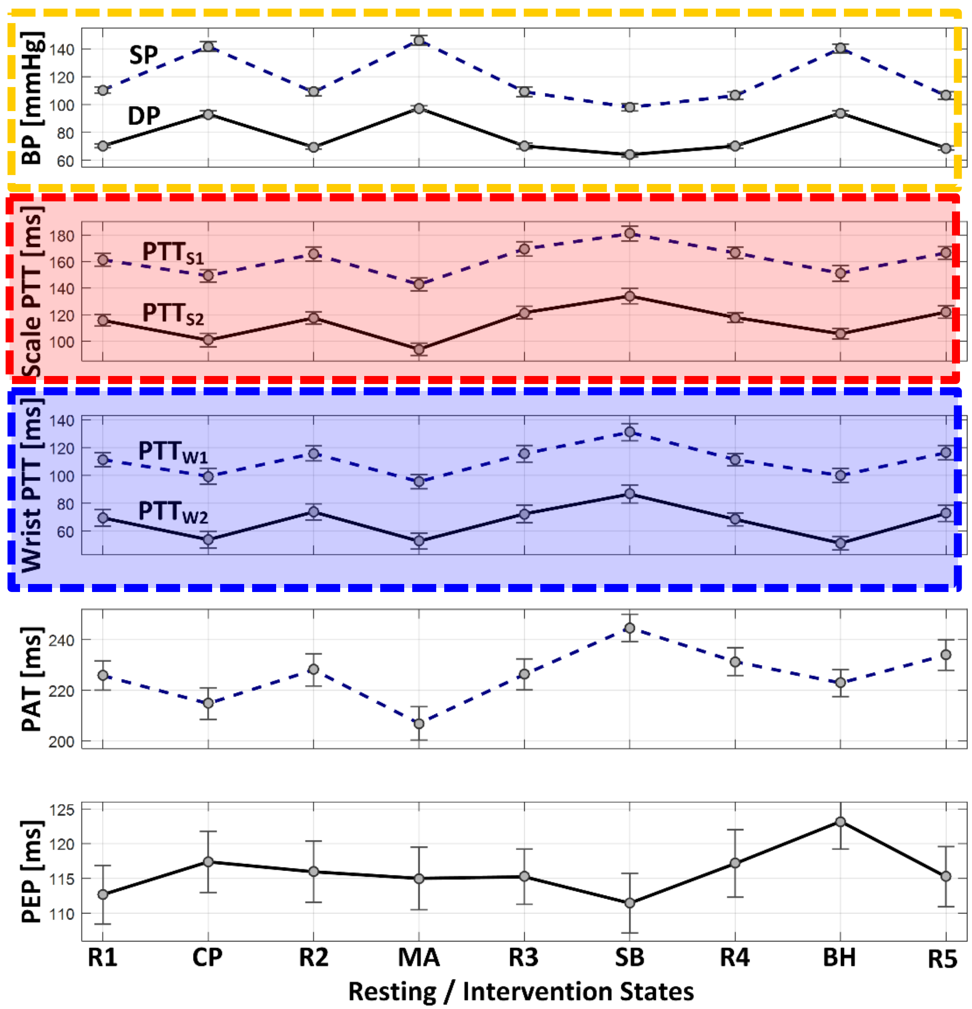
Kim et al., Scientific Reports (2016) / Yousefian et al., Scientific Reports (2019)

Ultra-Convenient Cuff-Less BP Monitoring via BCG

- 1st Principles-Guided BCG-Based PTT in Cuff-Less BP Monitoring



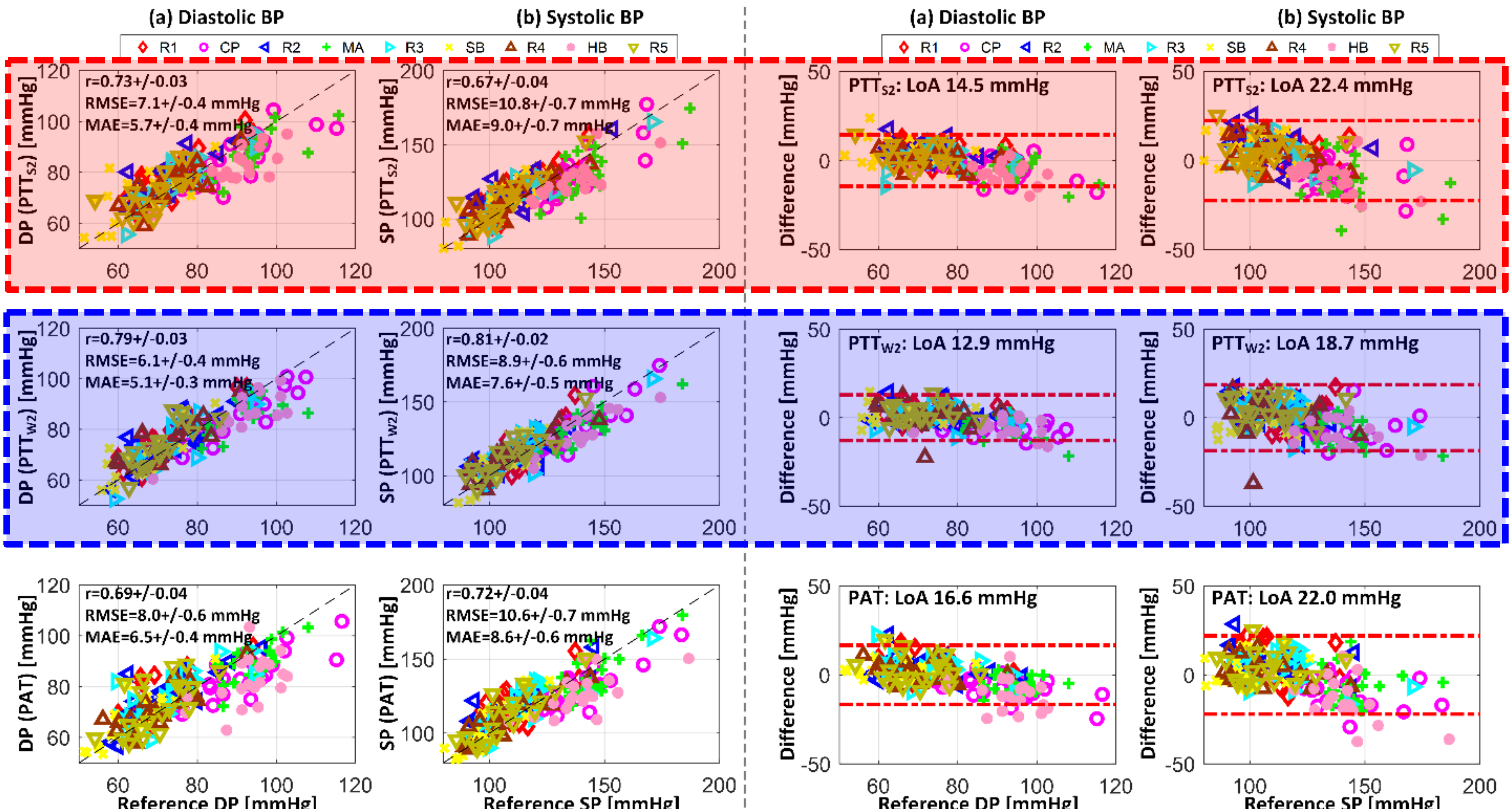




Yousefian et al., Scientific Reports (2019b)

Ultra-Convenient Cuff-Less BP Monitoring via BCG

- 1st Principles-Guided BCG-Based PTT in Cuff-Less BP Monitoring



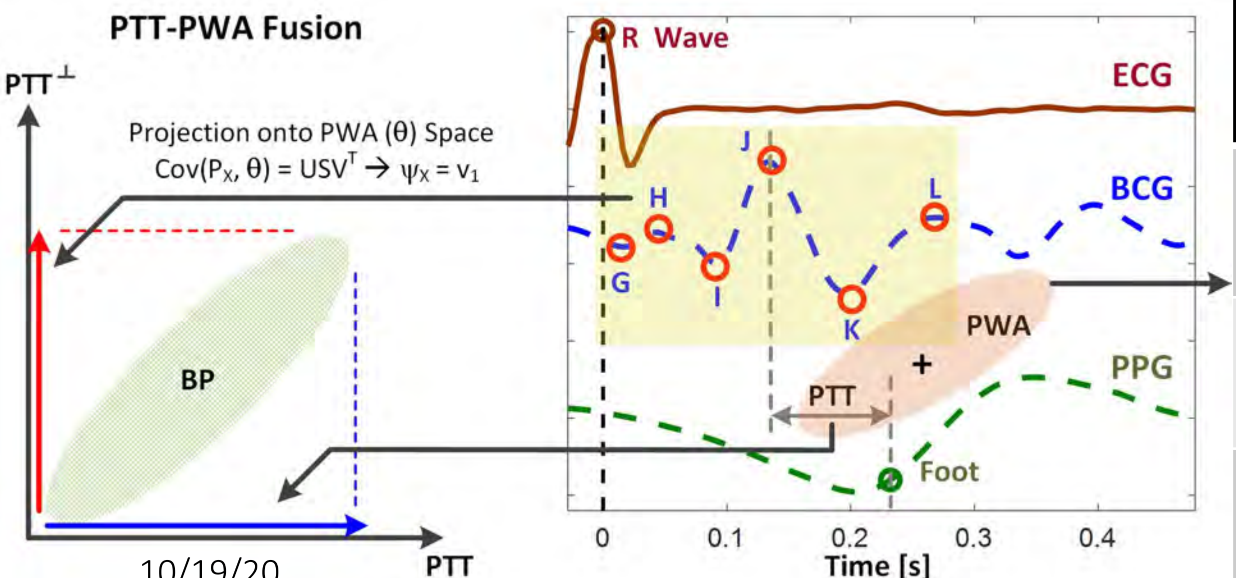
Yousefian et al., Scientific Reports (2019b)

Ultra-Convenient Cuff-Less BP Monitoring via BCG: PTT-Pulse Wave Analysis (PWA) Fusion

- Idea: To integrate PTT with additional waveform features in BCG and PPG supplementary to PTT

$$P_X = k_{X,1}\tau + K_{X,2}\psi_X(\boldsymbol{\theta}) + k_{X,3}$$

1) X = S (systolic), D (diastolic), P (pulse)
2) The predictor τ is PTT based on the BCG
3) The predictor $\psi_X(\boldsymbol{\theta})$ is a a function of fiducial points $\boldsymbol{\theta}$ in BCG and PPG

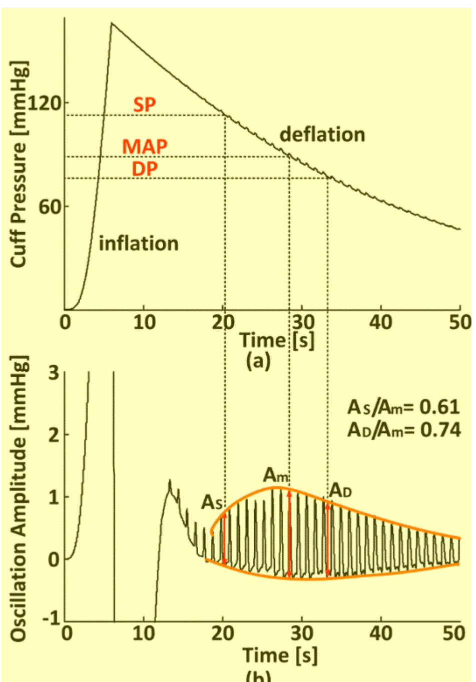


MAE [mmHg]	PTT	PTT-PWA
DP	5.5 (0.6)	4.9 (0.5)†
SP	7.9 (0.9)	7.4 (0.9)†
PP	4.5 (0.5)	3.6 (0.4)†

Yousefian et al., IEEE Access (2020)

Oscillometric BP Measurement: Low Accuracy Issue

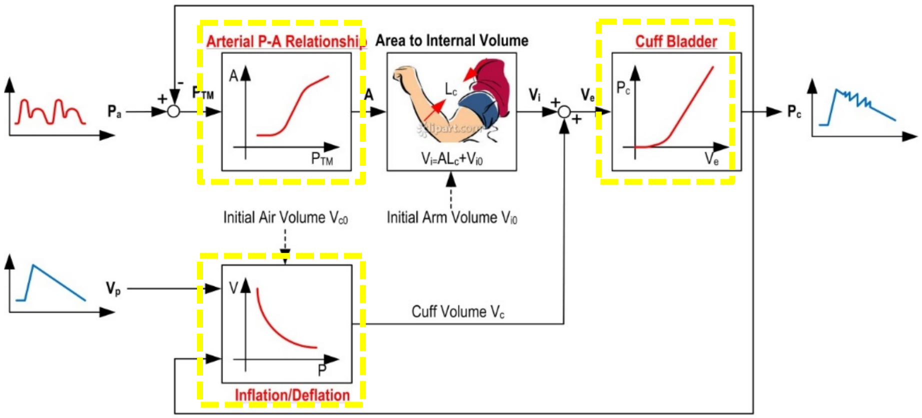
- Oscillometry is the most widely used method for cuff BP measurement
- Classical fixed-ratio method is population-based & prone to errors
- Even high-end oscillometric BP monitors exhibit poor accuracy



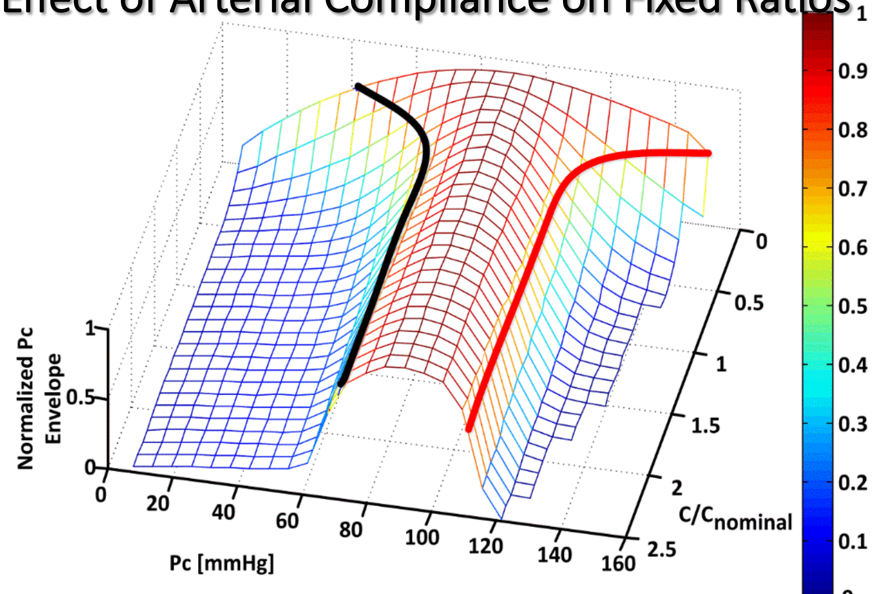
Device	Patient Type	BHS Grade	
SpaceLabs 90207 Natarajan et al., 1999	Preeclampsia	SP	D
		DP	D
IVAC Model 4200 Shuler et al., 1998	Hospital	SP	D
		DP	C
Philips MP90 Mireles et al., 2009	Neurosurgery	SP	D
		DP	C
Microlife Shih et al., 2013	Cardiac Catheterization	SP	C
		DP	C
Omron Shih et al., 2013	Cardiac Catheterization	SP	D
		DP	D
Dinamap 1846 XT Beaubien et al., 2002	Hypertension	SP	C
		DP	C

Elucidating Oscillometric BP Error Mechanisms

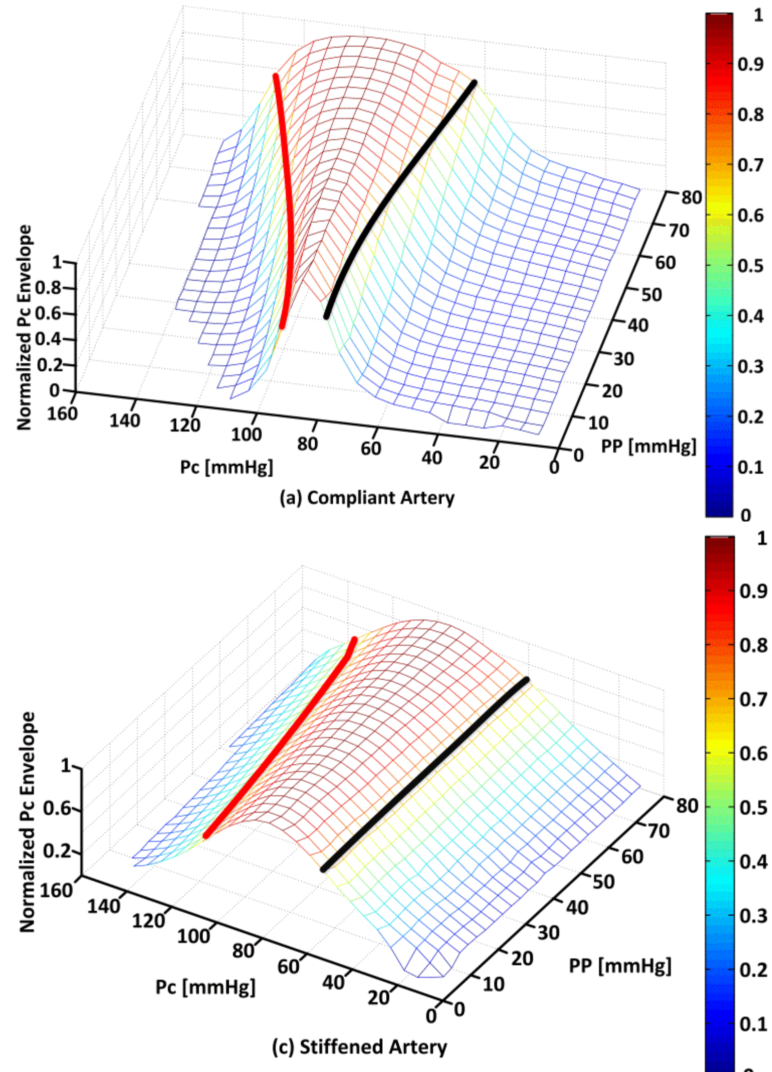
Oscillometric BP: Mathematical Model



Effect of Arterial Compliance on Fixed Ratios



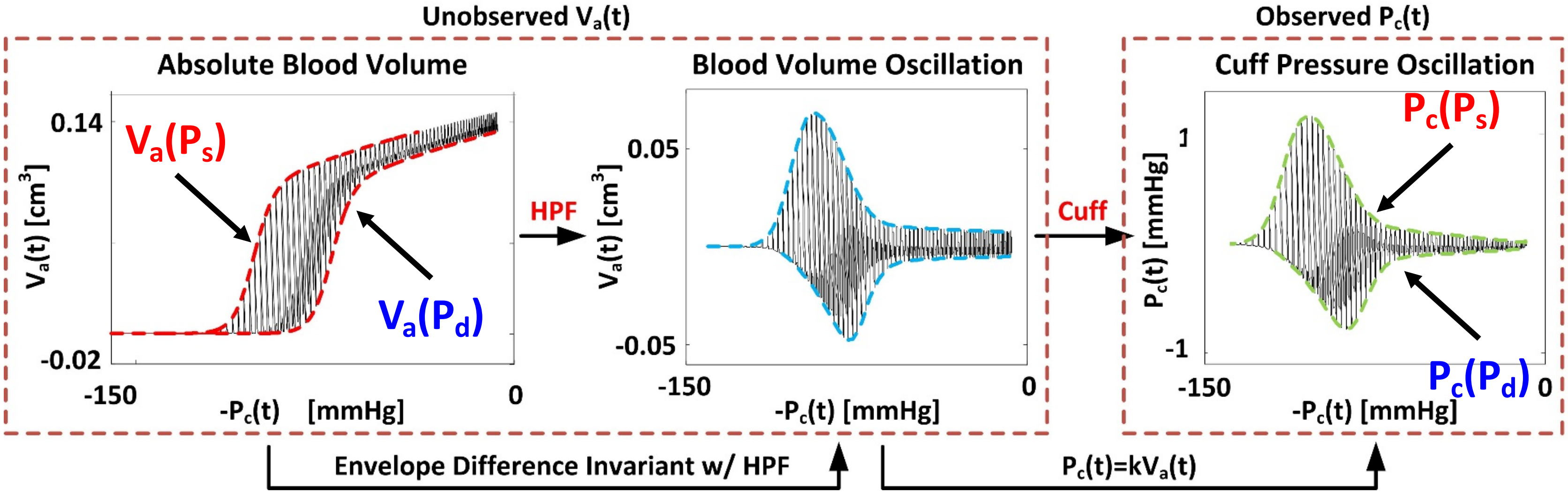
Effect of Pulse Pressure on Fixed Ratios



Liu et al., Annals of Biomedical Engineering (2013) / Chandrasekhar et al., Frontiers in Physiology (2019)

Patient-Specific Oscillometric BP Measurement

- Oscillometric BP Measurement Algorithm: Model-Based SYSID



Idea

To estimate patient-specific BP and arterial compliance by fitting a patient's oscillogram signal to a mathematical model of oscillometry

$$\min_{a,b,c,k,P_s,P_d} \left\| \left(P_c(P_s) - P_c(P_d)\right) - k\left(\hat{V}_a(P_s) - \hat{V}_a(P_d)\right) \right\|$$

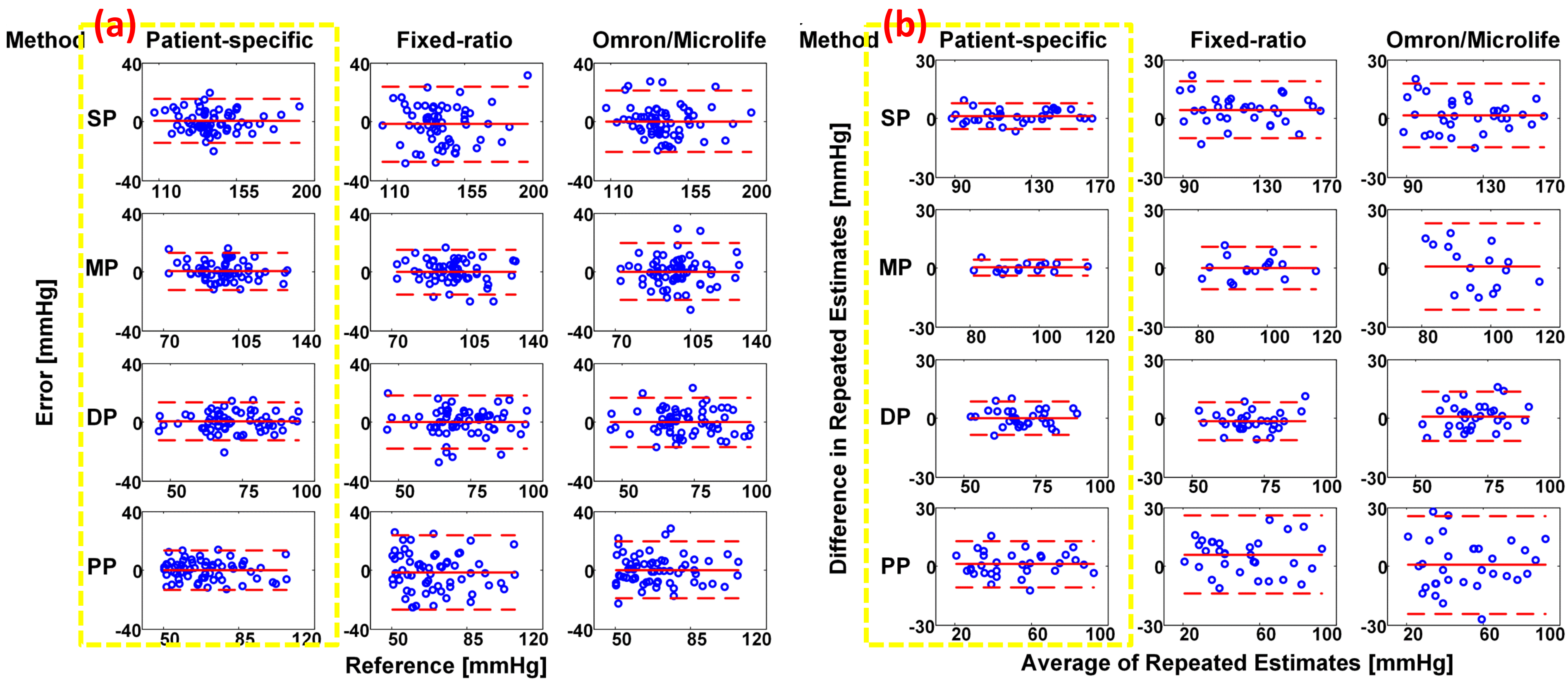
Measurements　　Model

Liu et al., IEEE Transactions on Biomedical Engineering (2016) / Liu et al., IEEE J. Translational Engineering in Health and Medicine (2017)

Patient-Specific Oscillometric BP Measurement

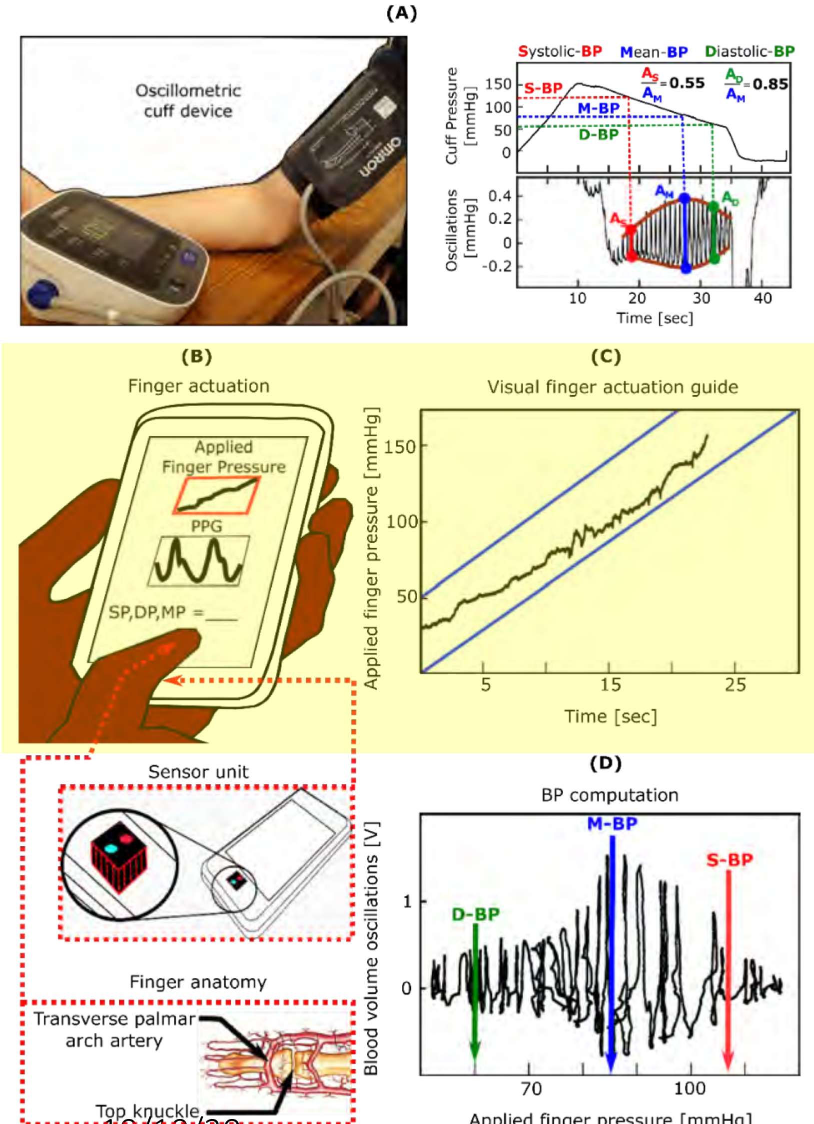
Blind Testing Results (145 Measurements from 88 Subjects): Precision & Repeatability

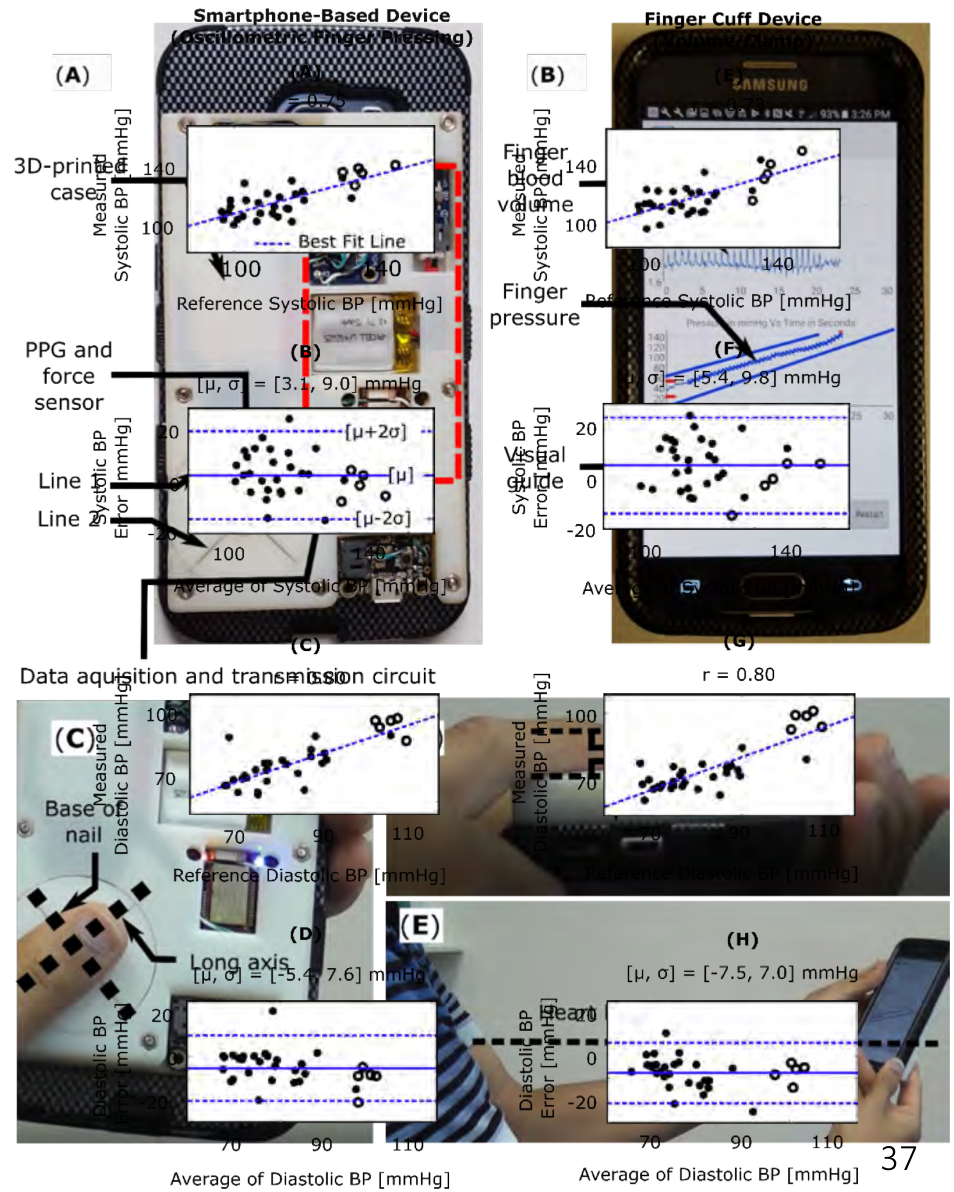
1) Comparable precision in normal PP group
2) Significantly superior precision in high PP group (a)
3) Patient-specific method achieved repeatability within AHA recommended limits (b)



Liu et al., IEEE Transactions on Biomedical Engineering (2016) / Liu et al., IEEE J. Translational Engineering in Health and Medicine (2017)

Smartphone-Based BP Monitoring

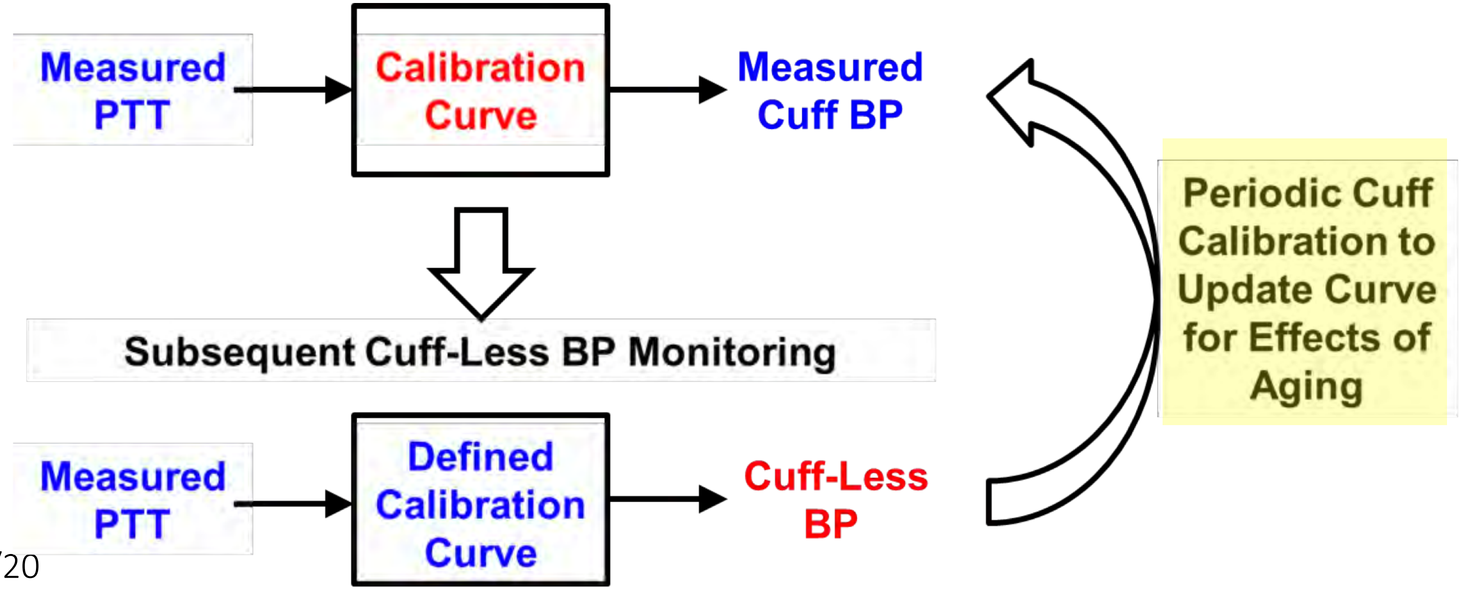




Chandrasekhar et al., Science Translational Medicine (2018)

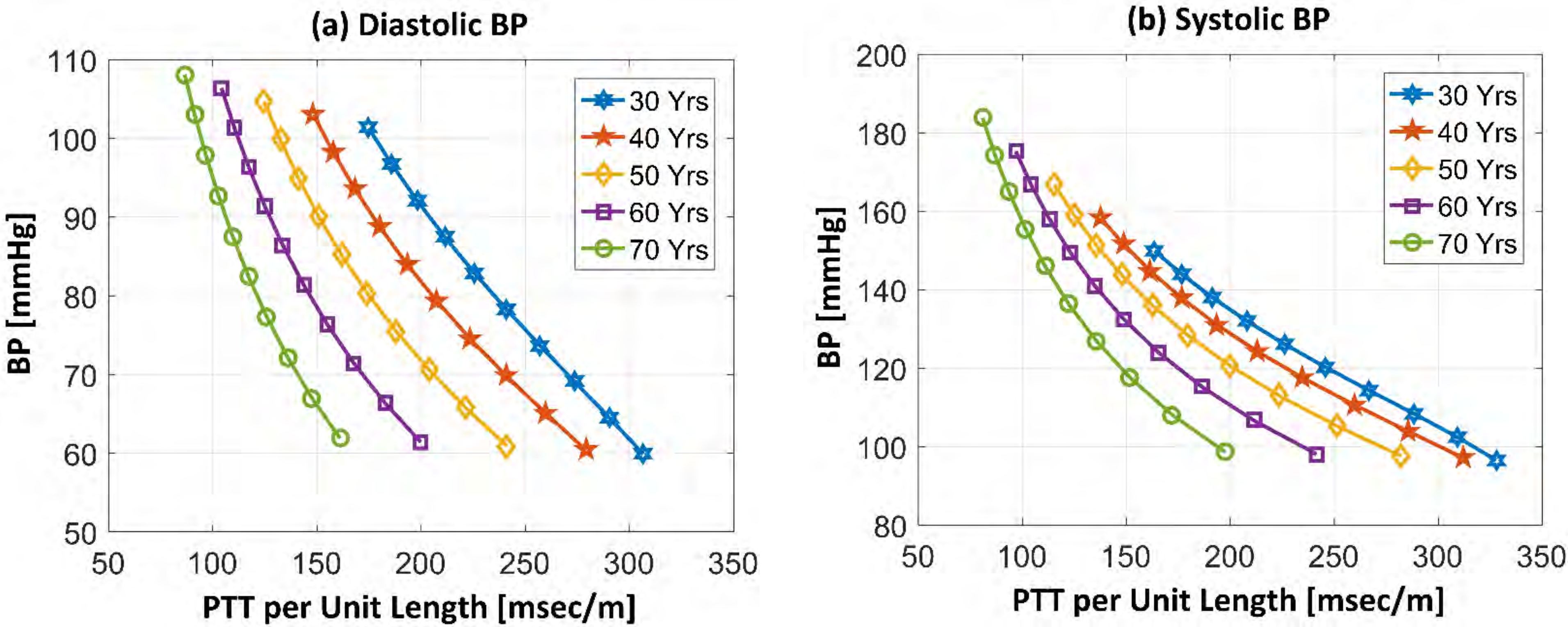
PTT-BP Relationship: Re-Calibration Period

- How often the PTT-BP calibration relationship must be updated?
- Evolution of PTT-BP Relationship
  1) Aging and disease → periodic update of PTT-BP model parameters
  2) PEP and SMC → fast-acting; compensation not reasonable/ even feasible
- It is obviously desirable to perform the cuff initializations as infrequently as possible. The question is: how infrequent can it be?



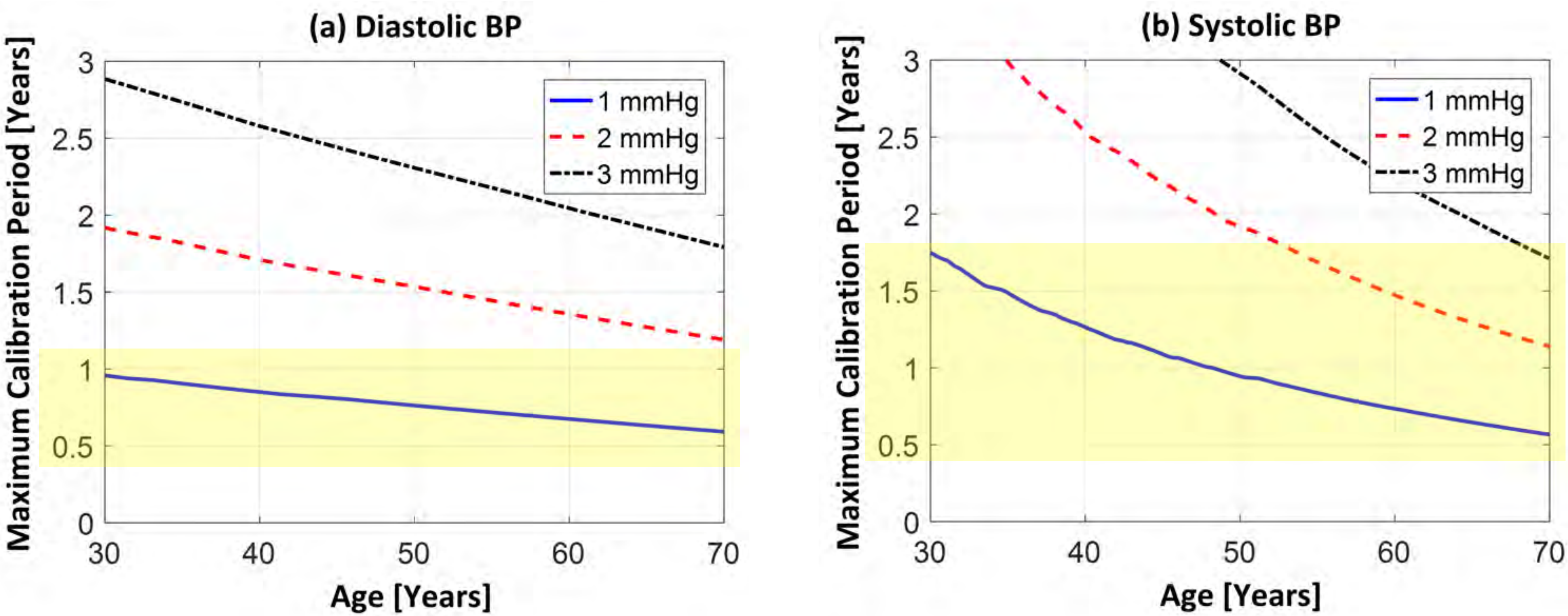
Re-Initialization Period

- One idea is to leverage mathematical models of PTT-BP relationship
- PTT-DP/SP relationship with age (B-H + Wesseling) → Theoretical prediction of re-calibration period



Re-Initialization Period

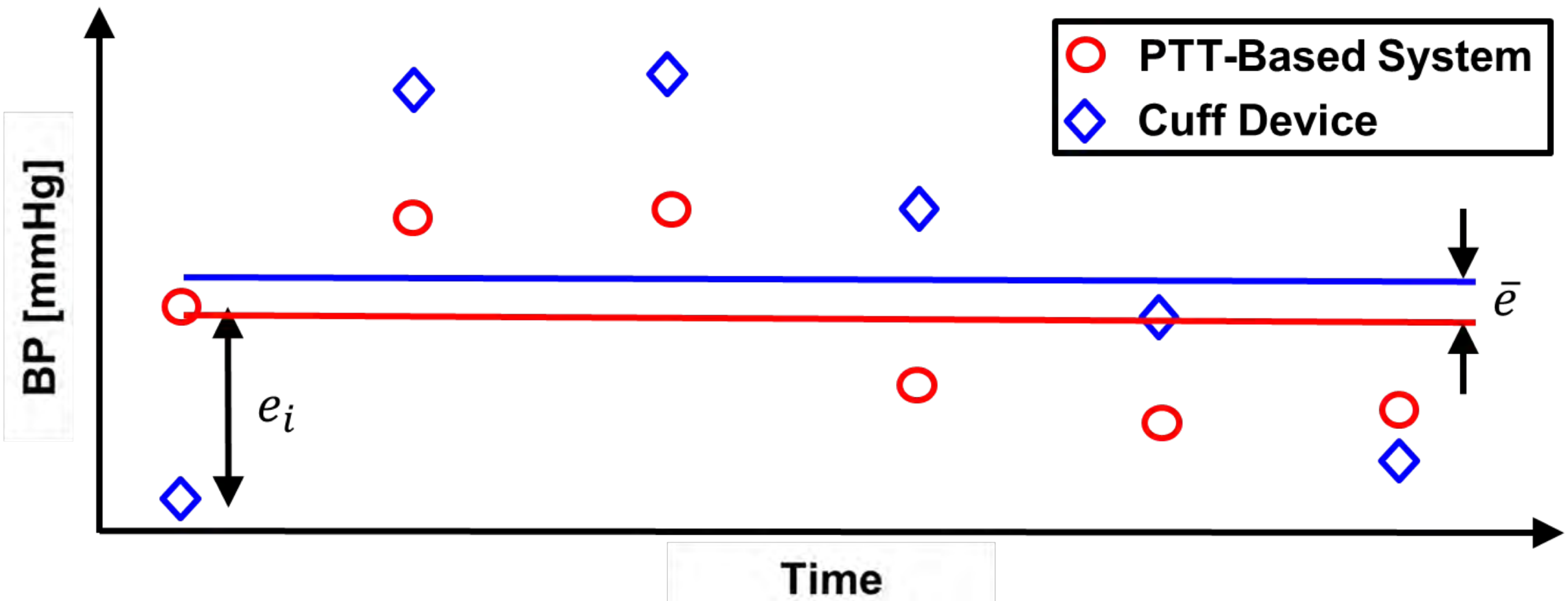
- The maximum calibration period to keep BP error < 1 mmHg is at least ~1 year for a 30 year old and declines linearly to ~6 months for a 70 year old.



Mukkamala et al., IEEE Transactions on Biomedical Engineering (2018)

Acceptable Error Limits in Cuff-Less BP Devices

- Cuff-less BP may not be as accurate as cuff-based BP (due to the imperfect calibration and confounders (e.g., SMC)). But, by affording a large number of measurements that can be averaged, cuff-less BP may still be valuable in hypertension screening despite large errors in individual measurements.



→ What is the acceptable limit of individual cuff-less BP errors to achieve accurate hypertension detection comparable to auscultation and oscillometry?

Within-Person BP Variability Model[1]

- 3-Way Nested ANOVA Model

$$P_{X,ijk} = \overline{P}_X + \tilde{P}_{X,i} + v_{P_X,ij} + e_{P_X,ijk}$$

1) $\overline{P}_X$: Population mean BP (X=S for SP and D for DP)
2) $\tilde{P}_{X,i} \sim \mathcal{N}\left(0, \sigma^2_{P_X}\right)$: Between-person variability
3) $v_{P_X,ij} \sim \mathcal{N}\left(0, \sigma^2_{v_{P_X}}\right)$: Between-visit variability for a specific person
4) $e_{P_X,ijk} \sim \mathcal{N}\left(0, \sigma^2_{e_{P_X}}\right)$: Within-visit variability for a specific person and visit

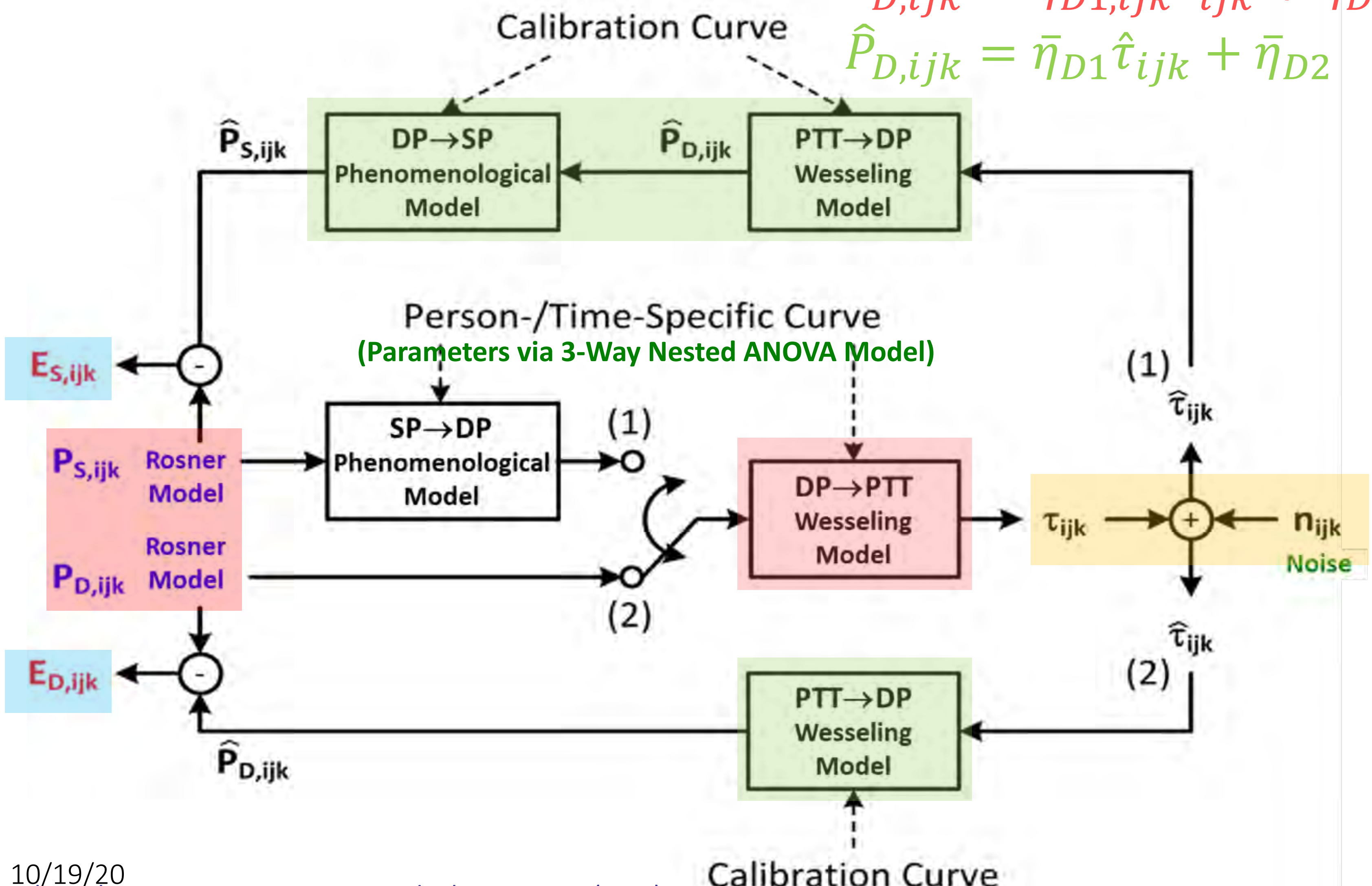
   - Systolic BP variability is greater than diastolic BP variability
   - Between-visit period variability is greater than within-visit period variability
   - Averaging single-visit cuff BP does not reduce between-visit period variability

[1]Rosner et al., American J. Epidemiology (1983)

Model-Based Acceptable Error Limits Analysis

$$P_{D,ijk} = \eta_{D1,ijk}\tau_{ijk} + \eta_{D2,ijk}$$

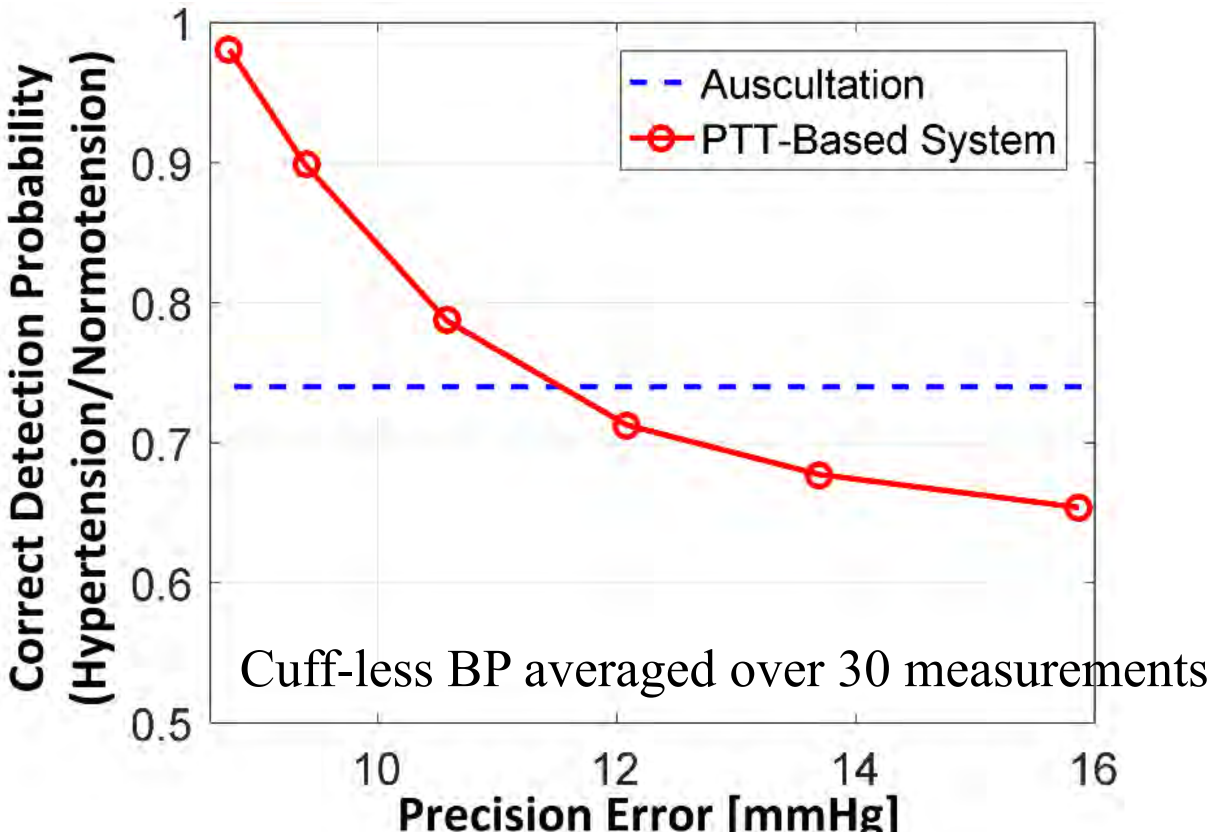
$$\hat{P}_{D,ijk} = \bar{\eta}_{D1}\hat{\tau}_{ijk} + \bar{\eta}_{D2}$$



Mukkamala et al., IEEE Transactions on Biomedical Engineering (2018)

Acceptable Error Limits: Auscultation as Reference

- SP precision limit: ~12 mmHg / DP precision limit: ~8 mmHg
- SP/DP bias: ~5 mmHg
- These predictions ignore auscultation error, white coat and masked effects, and nighttime measurements and may thus constitute lower bounds.



Mukkamala et al., IEEE Transactions on Biomedical Engineering (2018)

Acceptable Error Limits: Oscillometry as Reference

- The error in a PTT-based system w.r.t. an oscillometric device is expressed as the error in the PTT-based system w.r.t. auscultation minus the error in the oscillometric device w.r.t. auscultation:

$$\hat{P}_X - \hat{P}_{X,osc} = \underbrace{(\hat{P}_X - P_X)}_{A} - \overbrace{(\hat{P}_{X,osc} - P_X)}^{B}$$

1) A: Cuff-less BP error w.r.t. auscultation
2) B: Oscillometric BP error w.r.t. auscultation
3) A and B may not be highly correlated b/c the error sources associated with A and B are distinct

→ SP precision error limit can be up to ~14 [=$\sqrt{(12^2+8^2)}$] mmHg; DP precision limit can be up to ~11 [= $\sqrt{(8^2+8^2)}$] mmHg; and bias error limits can be up to 10 mmHg in magnitude!

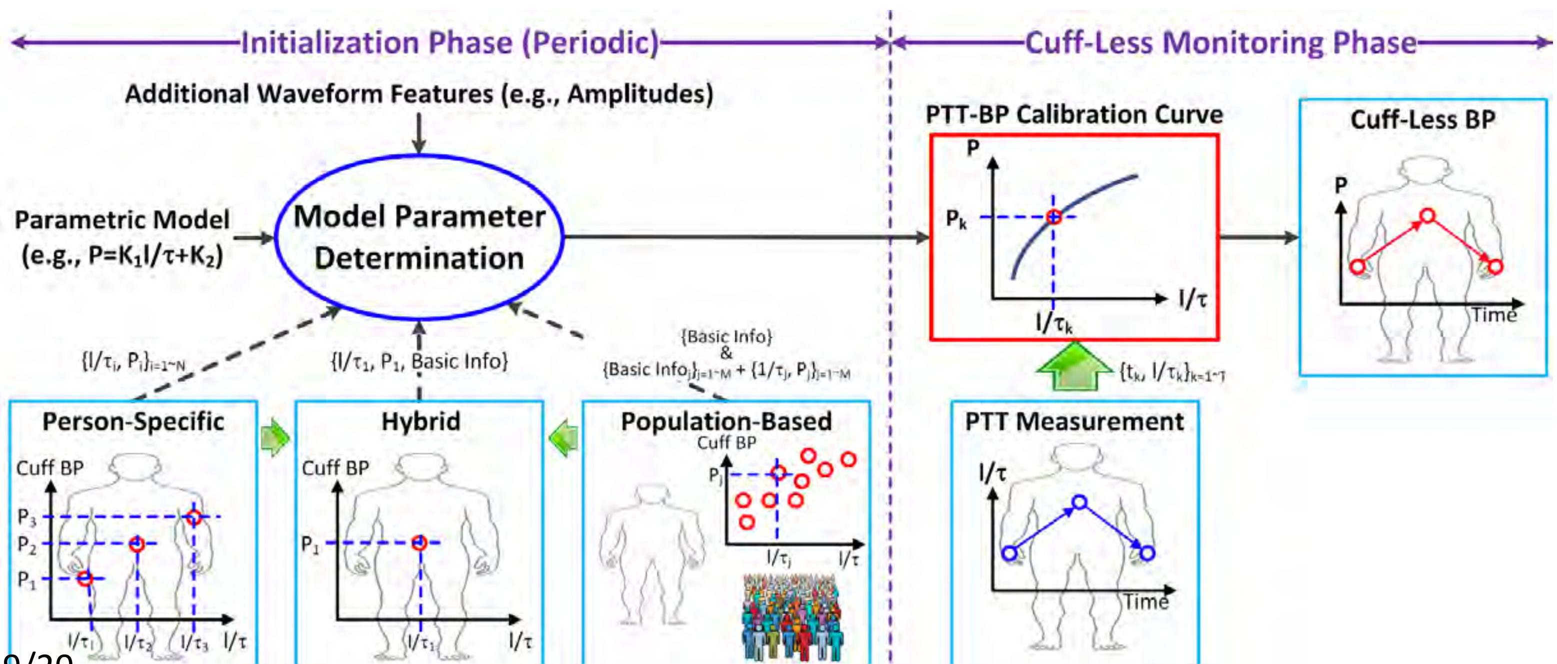
Mukkamala et al., IEEE Transactions on Biomedical Engineering (2018)

Acceptable Error Limits: Conclusions

- PTT-based systems w/ bias and precision errors > 5 mmHg and > 8 mmHg, especially with respect to automatic cuffs, should not be readily dismissed.
- The evaluation should be on a hypertension screening accuracy test rather than a measurement accuracy test.
- A running average of many BP measurements should be reported to indicate the true underlying BP of the person.

Cuff-Less Blood Pressure (BP) Monitoring via PTT

- Key Components:
  1) PTT measurement methods
  2) Parametric model relating PTT to BP
  3) Model parameter determination methods
  4) Re-calibration period & acceptable error limits



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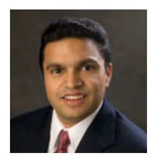

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