Influence of Non-Physiological Blood Pressure Artifacts on Cerebral Autoregulation

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JMM, 2017

Outline

1 Cerebral Autoregulation
- Biological Introduction
- Mathematical Introduction

2 Artifacts
- Implementation
- Effect on ARI

3 Conclusions and Further Directions

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Cerebral Autoregulation

Cerebral Autoregulation: Combination of various physiological processes modulating blood vessel properties in order to maintain constant cerebral blood flow despite changes in arterial blood pressure

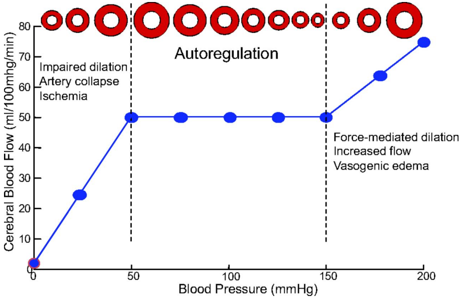
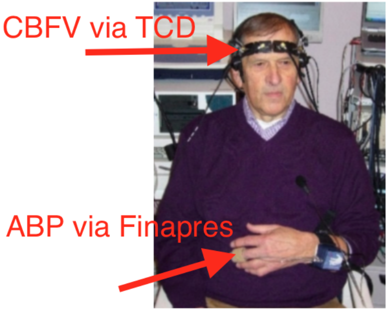


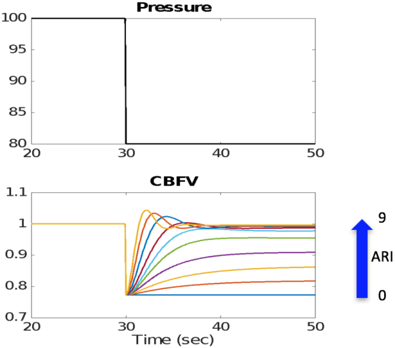
Figure: Cerebral Autoregulation Zone. Source: Pires, Paulo W., et al. "The effects of hypertension on the cerebral circulation." American Journal of Physiology-Heart and Circulatory Physiology 304.12 (2013): H1598-H1614.[4]

- Imparied Autoregulation seen in patients with:
  - stroke
  - head injuries
  - chronic hypertension
- Impaired Autoregulation is associated with
  - brain tissue injury by changes in blood pressure
  - disruption of blood-brain barrier
  - death

Cerebral Autoregulation

How to measure?



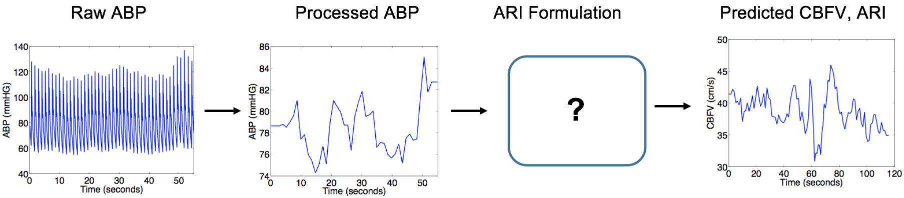


ARI: Autoregulation Index (clinical tool) measures how well cerebral autoregulation is occurring

0	$\rightarrow$	9
No Autoregulation		Best Autoregulation

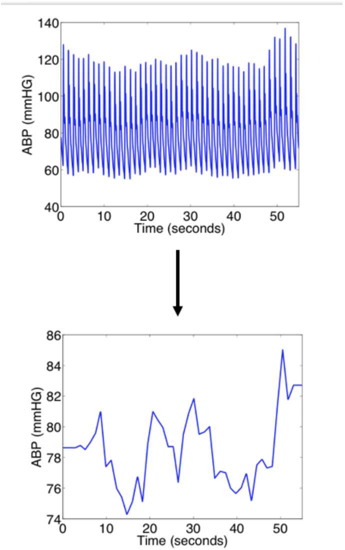
ARI

How to measure?



- Raw ABP signals are pre-processed to obtain a beat-to-beat average
- ARI is calculated using processed ABP and produces predicted CBFV

Data and Processing



- 36 one-minute baseline ABP and CBFV readings of normotensive subjects
- low-pass filtered using zero-phase 4th-order Butterworth filter in both directions with cutoff frequency of 20 Hz
- beat-to-beat detection
- downsampled to 10 Hz for uniform signals

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Tiecks et. al [5] formulated the following phenomenological model:

$$dP = \frac{P - P_m}{P_m - P_{cr}}$$

$$x_2 = x_2 + \frac{x_1 - 2Dx_2}{fT}$$

$$x_1 = x_1 + \frac{dP - x_2}{fT}$$

$$\hat{V}(T, D, K) = V_m\,(1 + dP - Kx_2)$$

$$ARI = \min_{ARI \in [0,9]} ||\hat{V}(T, D, K) - CBFV||$$

ARI	T	D	K
0	2	0	0
1	2	1.60	0.20
2	2	1.50	0.40
3	2	1.15	0.60
4	2	0.90	0.80
5	1.9	0.75	0.90
6	1.6	0.65	0.94
7	1.2	0.55	0.96
8	0.87	0.52	0.97
9	0.65	0.50	0.98

where P - ABP input, P_m - mean ABP

$\hat{V}$ - CBFV output, V_m - mean CBFV

f - sampling frequency

P_{cr} - critical pressure (12 mmHG)

Mathematical Model

Variations

Tiecks et. al [5] model was not specific of time points for x_1 and x_2:

$$dP(t) = \frac{P(t) - P_m}{P_m - P_{cr}}$$

$$\hat{V}(t) = V_m \left(1 + dP - Kx_2(t)\right)$$

Panerai et. al 1999 [3]

$$x_1(t) = x_1(t-1) + \frac{\mathbf{dP(t)} - x_2(t-1)}{fT}$$

$$x_2(t) = x_2(t-1) + \frac{\mathbf{x_1(t)} - 2Dx_2(t-1)}{fT}$$

Panerai 2010 et. al [1]

$$x_1(t) = x_1(t-1) + \frac{\mathbf{dP(t-1)} - x_2(t-1)}{fT}$$

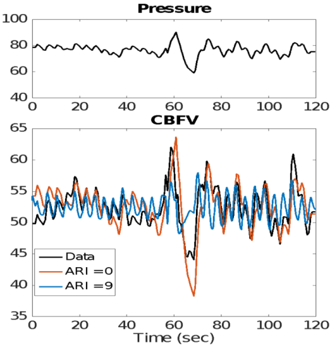
$$x_2(t) = x_2(t-1) + \frac{\mathbf{x_1(t-1)} - 2Dx_2(t-1)}{fT}$$

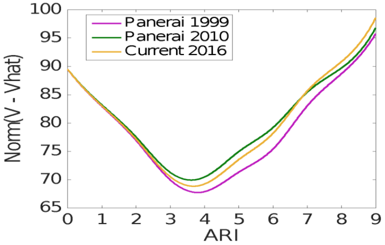
Current Formulation

$$x_1(t) = x_1(t-1) + \frac{\mathbf{dP(t)} - x_2(t-1)}{fT}$$

$$x_2(t) = x_2(t-1) + \frac{\mathbf{x_1(t-1)} - 2Dx_2(t-1)}{fT}$$

We observe little difference between the various formulations for models, so we stick with the 2016 “current” model





1999 → ARI of 3.80
2010 → ARI of 3.61
2016 → ARI of 3.68

$$\begin{aligned}
dP(t) &= \frac{P(t) - P_m}{P_m - P_{cr}} \\
x_1(t) &= x_1(t-1) + \frac{dP(t) - x_2(t-1)}{fT} \\
x_2(t) &= x_2(t-1) + \frac{x_1(t-1) - 2Dx_2(t-1)}{fT} \\
\hat{V}(t, T, D, K) &= V_m\left(1 + dP - Kx_2(t)\right) \\
ARI &= \min_{ARI \in [0,9]} ||\hat{V}(t, T, D, K) - CBFV(t)||
\end{aligned}$$

where

P - ABP input, P_m - mean ABP

$\hat{V}$ - CBFV output, V_m - mean CBFV

f - sampling frequency

P_{cr} - critical pressure (12 mmHG)

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ABP Measurement

Setup

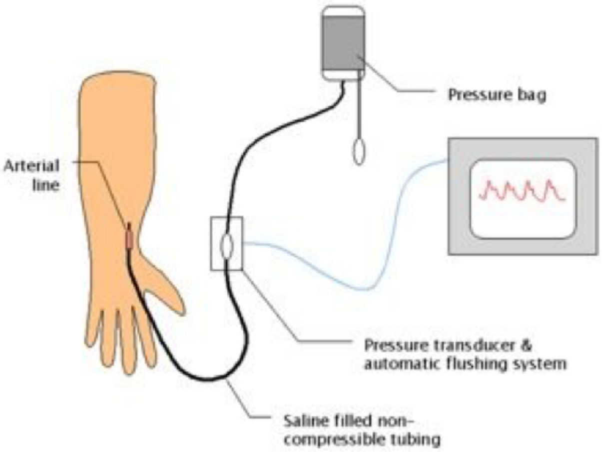


Figure: ABP measurement set-up. Source: "Arterial Line and Intra-arterial Blood Pressure Monitoring." Life in the Fast Lane Medical Blog. 14 June 2015. Web. 03 Jan. 2017

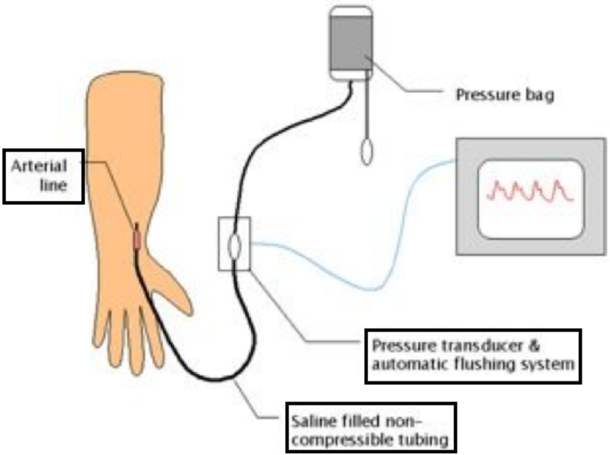


Figure: Where non-physiological artifacts can occur in ABP measurement.

Source: "Arterial Line and Intra-arterial Blood Pressure Monitoring." Life in the Fast Lane Medical Blog. 14 June 2015. Web. 03 Jan. 2017

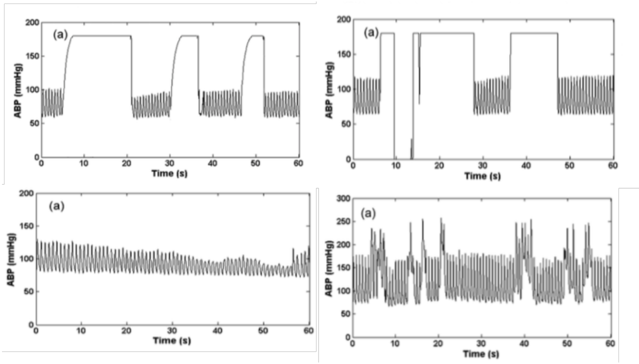
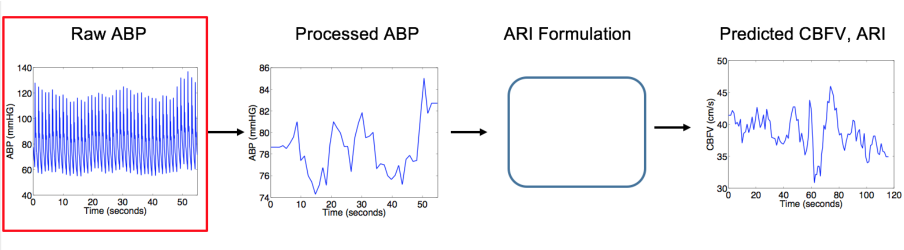


Figure: Real examples of non-physiological artifacts in ABP measurements.
Source: Li, Qiao et. al. "Artificial arterial blood pressure artifact models and an evaluation of a robust blood pressure and heart rate estimator." Biomedical engineering online 8.1 (2009):.[2]



Only raw ABP data is altered to include non-physiological artifacts

CBFV data is not altered!

Non-Physiological Artifacts

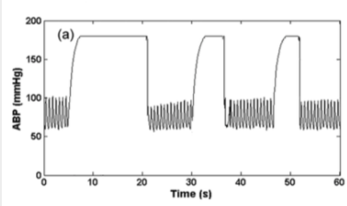
Implementation

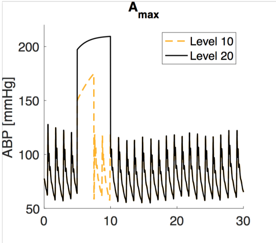
- Each artifact is inserted in to the raw ABP measurements 5 seconds into the time series
- Severity of artifacts are measured in 'levels' where level 0 corresponds to no artifact and level 20 corresponds to maximal artifact.
- For each artifact formulation, there may be multiple parameters governing the shape of the artifact. Upper and lower bounds will be given for each parameter. Levels 0-20 correspond to linearly increasing all parameters from their lower to upper bounds

Artifact 1

Saturation to maximal ABP

$$A_{max}(\alpha, L, P_{max}) = \tanh(\alpha \pi t)(P_{max} - P_{dias}) + P_{dias}$$



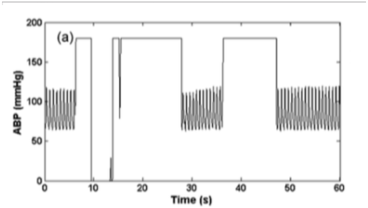


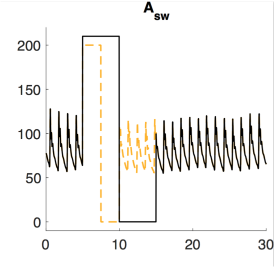
Parameter	Lower Bound	Upper Bound	Meaning
α	0	0.1	saturation rate
P_{max} (mmHG)	190	210	maximal ABP
L (s)	0	5	total time of artifact

Artifact 2

Square Wave Pulse

$$A_{sw}(P_{\max}, L) = \begin{cases} P_{\max} & t \in [0, L/2] \\ 0 & t \in [L/2, L]. \end{cases}$$



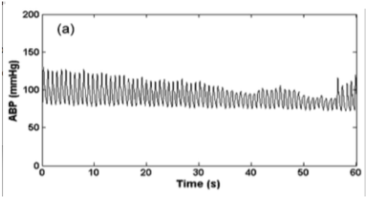


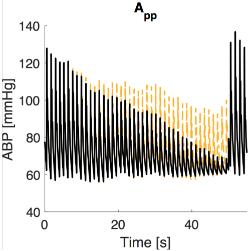
Parameter	Lower Bound	Upper Bound	Meaning
$P_{\max}$ (mmHG)	190	210	maximal ABP
L (s)	0	10	total time of artifact

Artifact 3
Pulse Pressure Reduction

Reduces systolic pressure linearly over the span of 45 seconds to the value

$$P_{\text{end}} = MP_{\text{sys}}$$





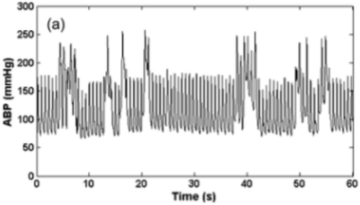
Parameter	Lower Bound	Upper Bound	Meaning
M	1	0.1	ratio at end of artifact

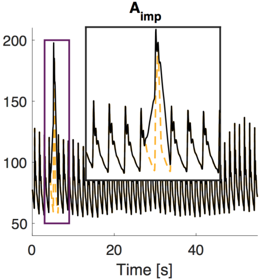
Artifact 4

Impulse

$$f_L = \begin{cases} \dfrac{L\sin(2\pi t/L)}{2\pi t} & t \in [-L/2, L/2] \\ 0 & \text{otherwise.} \end{cases}$$

$$A_{\text{imp}}(L) = P + (P_{\text{sys}} - P_{\text{dia}})\, f_L, \qquad t \in [-L/2, L/2]$$





Parameter	Lower Bound	Upper Bound	Meaning
L (s)	0	2	total time of artifact

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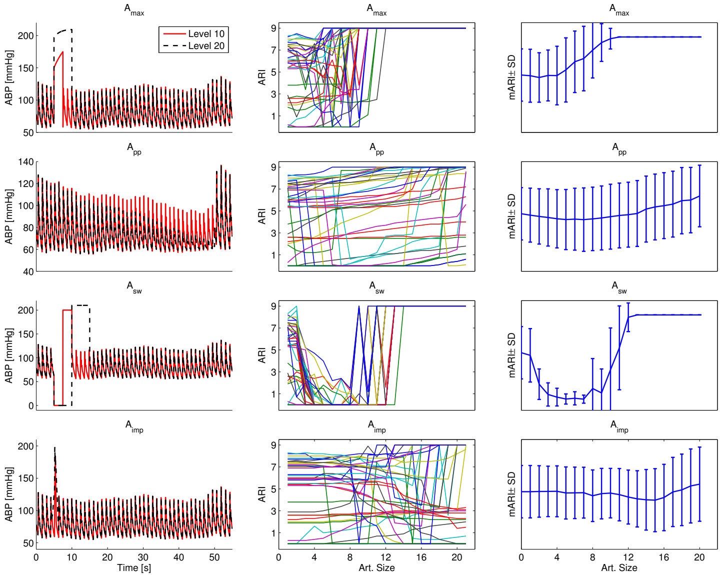
Artifact Effects



Definition

The *critical artifact size* is the level of artifact which generates a change of 10% change in the mean ARI of all patients.

Artifact	Critical size	Parameters		
A_{max}	5.21 ± 2.1	L=1.3 s	$P_{max} = 195.2\,mmHg$	$\alpha = 0.026$
A_{sw}	2.75 ± 2.1	L=1.4 s	$P_{max} = 192.8\,mmHg$	
A_{pp}	8.06 ± 5.1	M = 0.64		
A_{imp}	11.52 ± 3.9	L=1.05 s		

Table: The mean critical artifact size $\pm$ standard deviation and the corresponding parameters that generate it.

Conclusions and Further Directions

- ARI values can be sensitive to non-physiological artifacts present in data.
- Saturation to maximal ABP and square wave pulses will *always* predict an ARI value of 9 if present long enough.
- Reduced pulse pressure and impulse artifacts are not as sensitive but can still change ARI values up to 10% if present long enough.
- Further Directions
  - Sensitivity of parameters of artifacts
  - How do multiple artifacts or repetition change ARI values?
  - Implement detection system to filter out nonphysiological artifacts
  - Hypertensive vs. normotensive

Acknowledgements

Group 1 Participants:

- P. Sang Chalacheva
- Katrina Johnson
- Greg Mader
- Kevin O'Keeffe

Grant Number: 1321794

Works Cited I

Dineen, Nicky E and Brodie, F G and Robinson, Thompson G and Panerai, Ronney B.
Continuous estimates of dynamic cerebral autoregulation during transient hypocapnia and hypercapnia.
Journal of applied physiology, 108(3):604–613, 2010.

Li, Qiao and Mark, Roger G and Clifford, and Gari D.
Artificial arterial blood pressure artifact models and an evaluation of a robust blood pressure and heart rate estimator.
Biomedical Engineering Online, 8(1):2009.

Panerai, Ronney B and Dawson, Suzanne L and Potter, and John F.
Linear and nonlinear analysis of human dynamic cerebral autoregulation.
American Journal of Physiology-Heart and Circulatory Physiology, 277(3): H1089–H1099, 1999.

Pires, Paulo W and Ramos, Carla M Dams and Matin, Nusrat and Dorrance, and Anne M.
The effects of hypertension on the cerebral circulation.
American Journal of Physiology-Heart and Circulatory Physiology, 204(12):H1598–H1614, 2013.

Tiecks, Frank P and Lam, Arthur M and Aaslid, Rune and Newell, and David W.
Comparison of static and dynamic cerebral autoregulation measurements.
Stroke, 26(6):1014–1019, 1995.