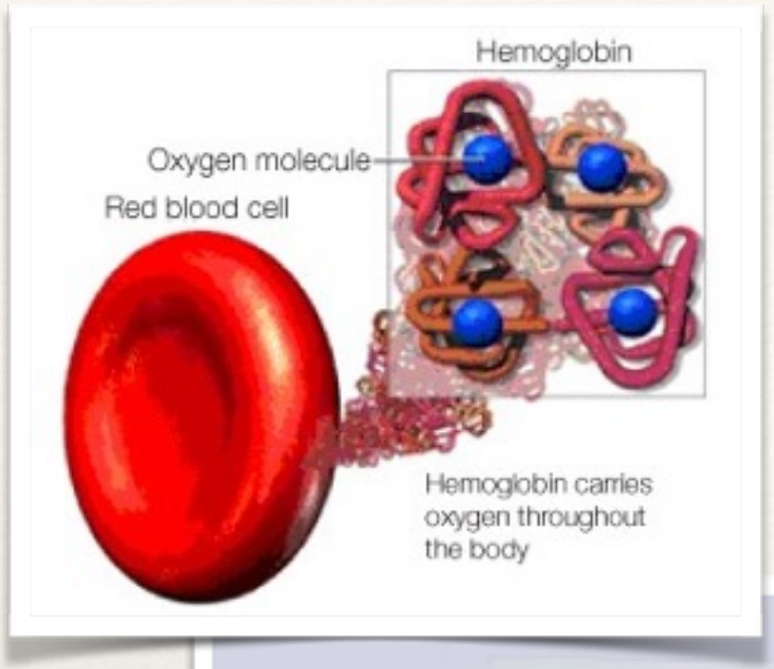
Systems and Computer Engineering, Carleton University

Signal Quality Analysis in Pulse Oximetry: Modelling and Detection of Motion Artifact

Geoffrey Clarke

Thesis Defence
M.A.Sc. Biomedical Engineering

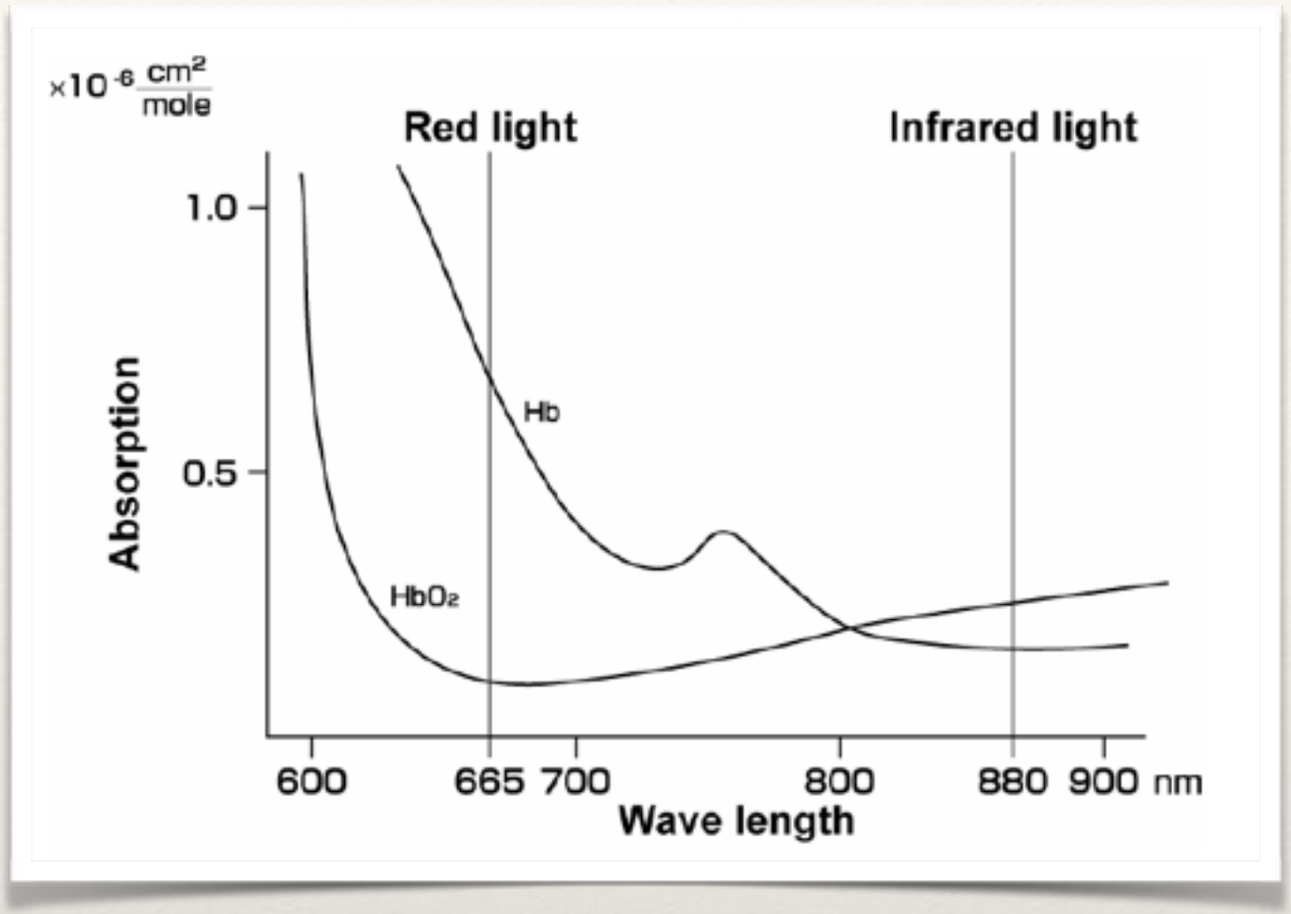
Supervisors: Dr. Adrian Chan and Dr. Andy Adler

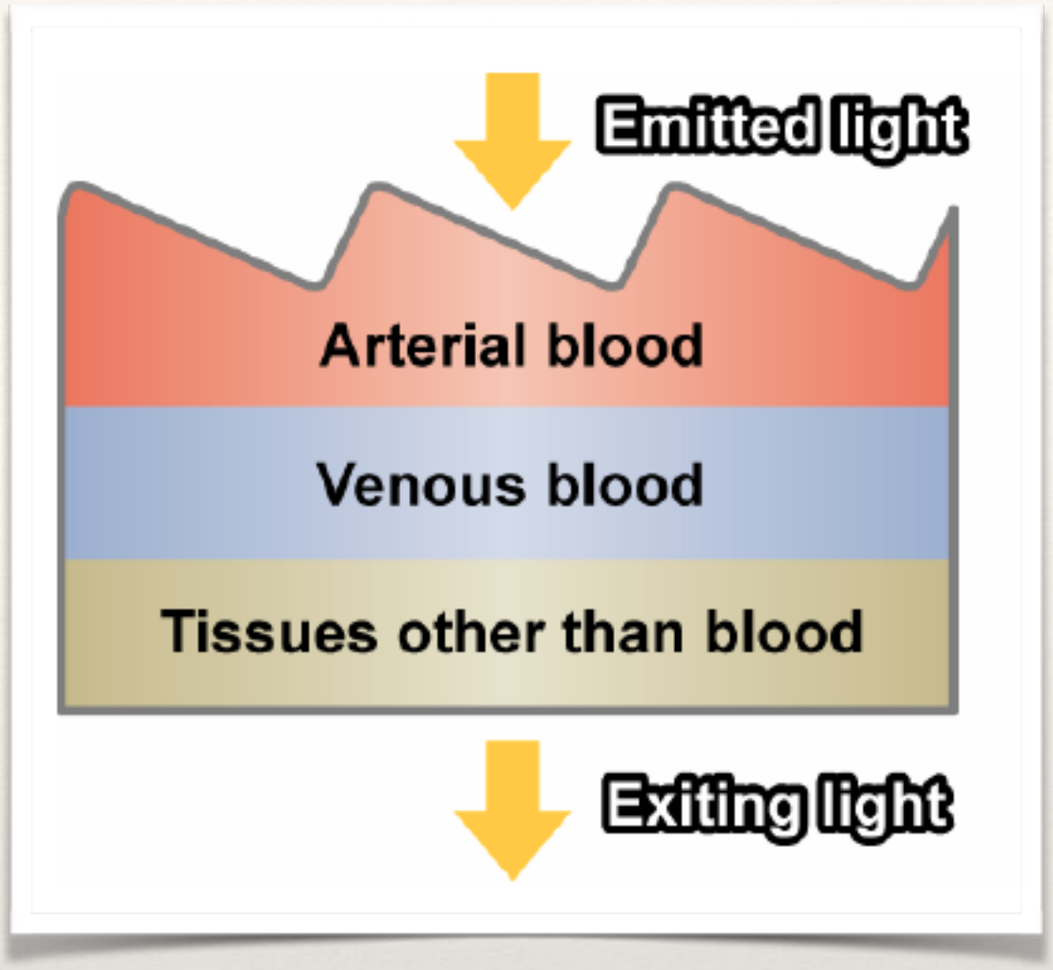


- Anaesthesia monitoring
- Cardio-pulmonary assessment
- Sleep apnea assessment
- Athlete training - altitude

Background

How much oxygen is in my patient's blood?
Why do we care?





Images: Konica Minolta sensing, "Basic understanding of the pulse oximeter"

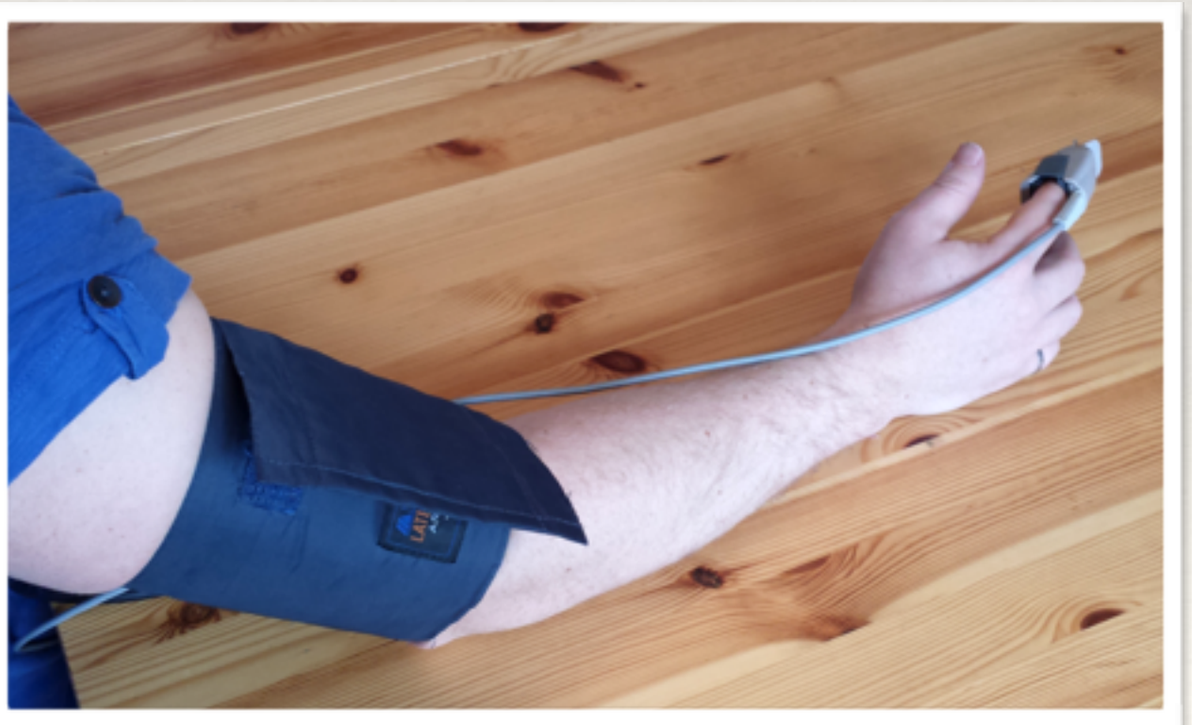
Background

Absorption spectra and origin of the photoplethysmograph waveform

Motivation

- 77% False alarm rate in PACU (Wiklund et al.)
- 93% False alarm rate in PICU (Lawless et al.)
- Despite research in motion artifact mitigation, dealing with unusable data is rarely addressed (Lovell et al.)
- Inadequate alarms are THE top health technology hazard (ECRI Institute)

Data Collection Methodology



Summary of Contributions

- Evaluation of measurement error during motion
- Analytical modelling of pulse oximetry motion artifact
- Development and evaluation of automatic signal quality assessment

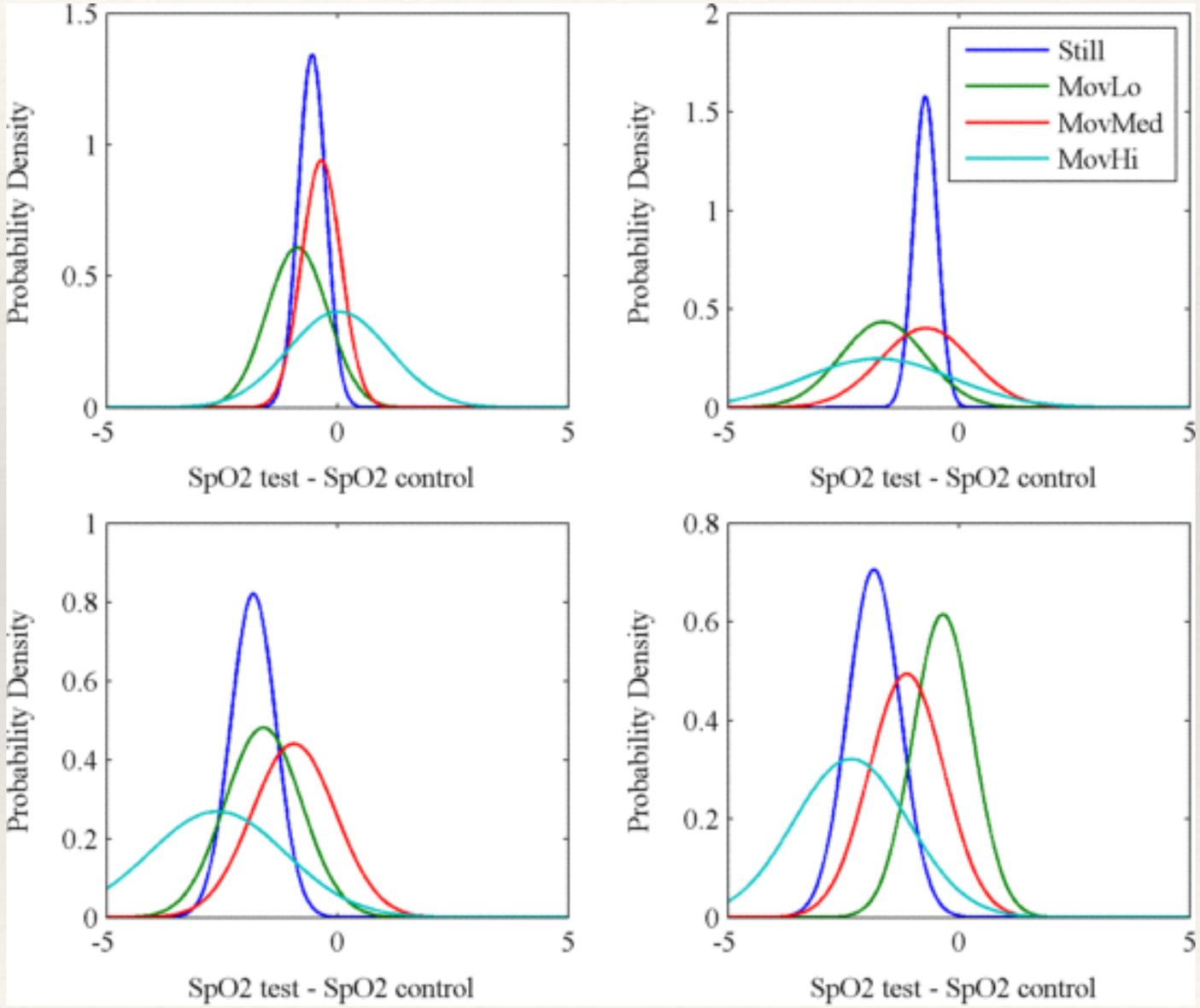
Contribution 1:

Evaluation of SpO2 measurement error during motion

- Test for motion-induced bias and variance at three different “levels” of motion
- Quantify relationship between bias/variance and true SNR in artificially contaminated signals

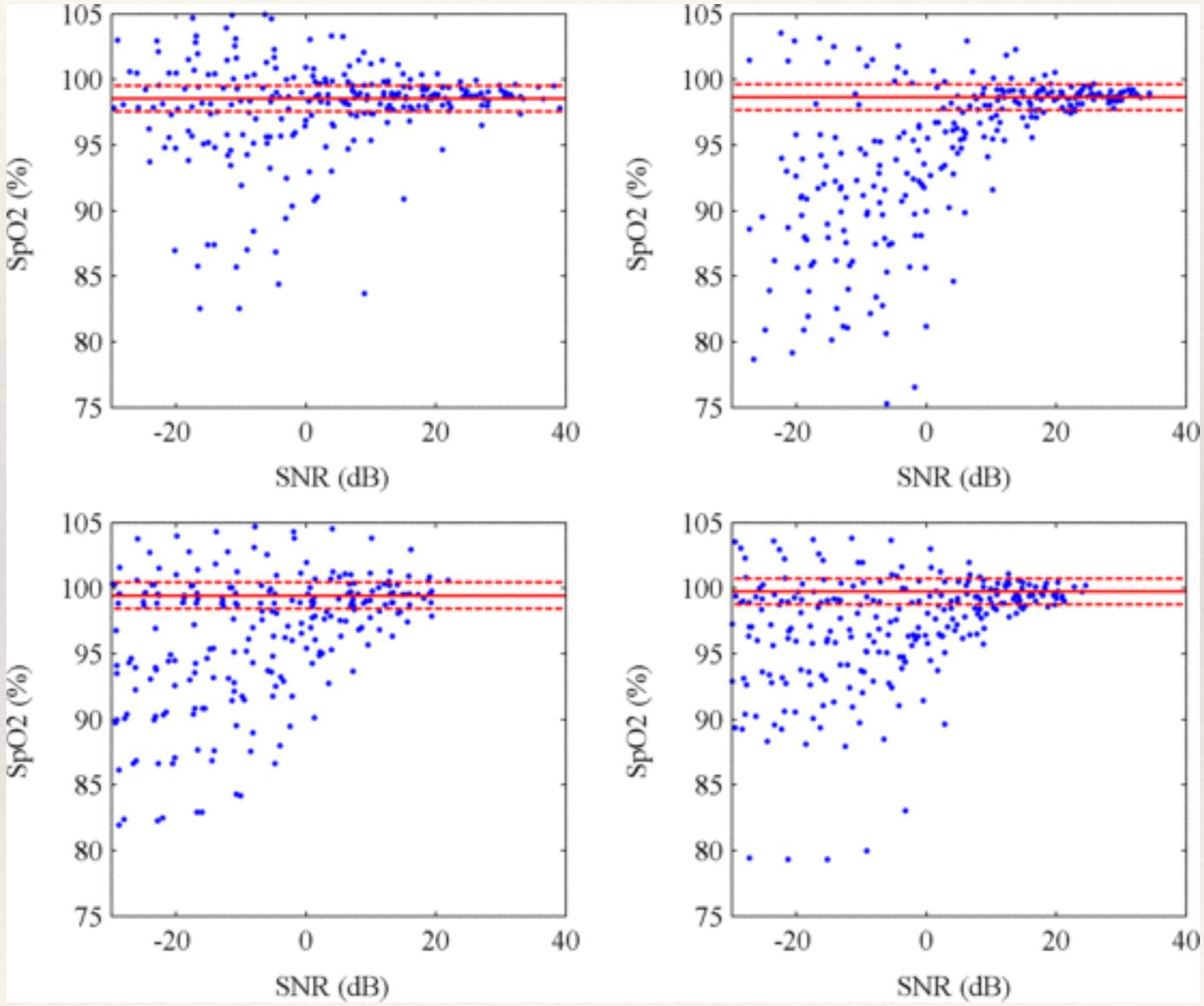
Results - Real Data

- Strong evidence for increase in measurement variance during motion
- Evidence that bias is possible - but not necessarily negative



Results - Artificially Contaminated Data

- Evidence for increase in measurement variance at low SNR
- Evidence for negative SpO2 bias at low SNR



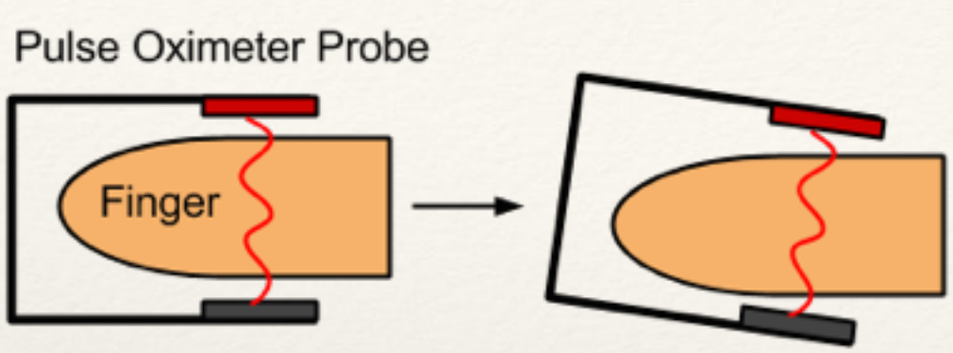
Summary

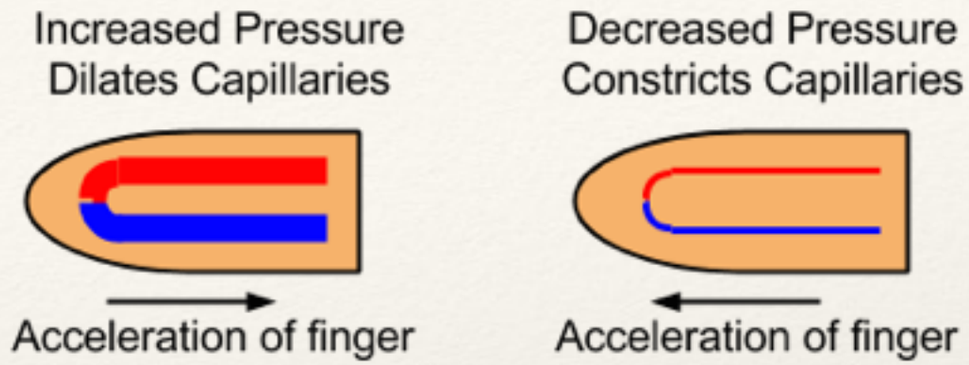
- Real and artificial data showed variance increase
- Real data showed SpO2 bias sometimes, but did not support previous claims of negative SpO2 bias
- Artificial data supported claims of negative SpO2 bias
- Inconsistency may be due to differences in motion artifact generation methodology

Contribution 2:

Analytical modelling of pulse oximetry motion artifact

- Assume R is a combination of R_S and R_N - as SNR decreases, R approaches R_N
- Propose two models and derive R_N associated with each
- Compare with characteristics of isolated noise data





$$R_N = \frac{\varepsilon_{Red}}{\varepsilon_{IR}}$$

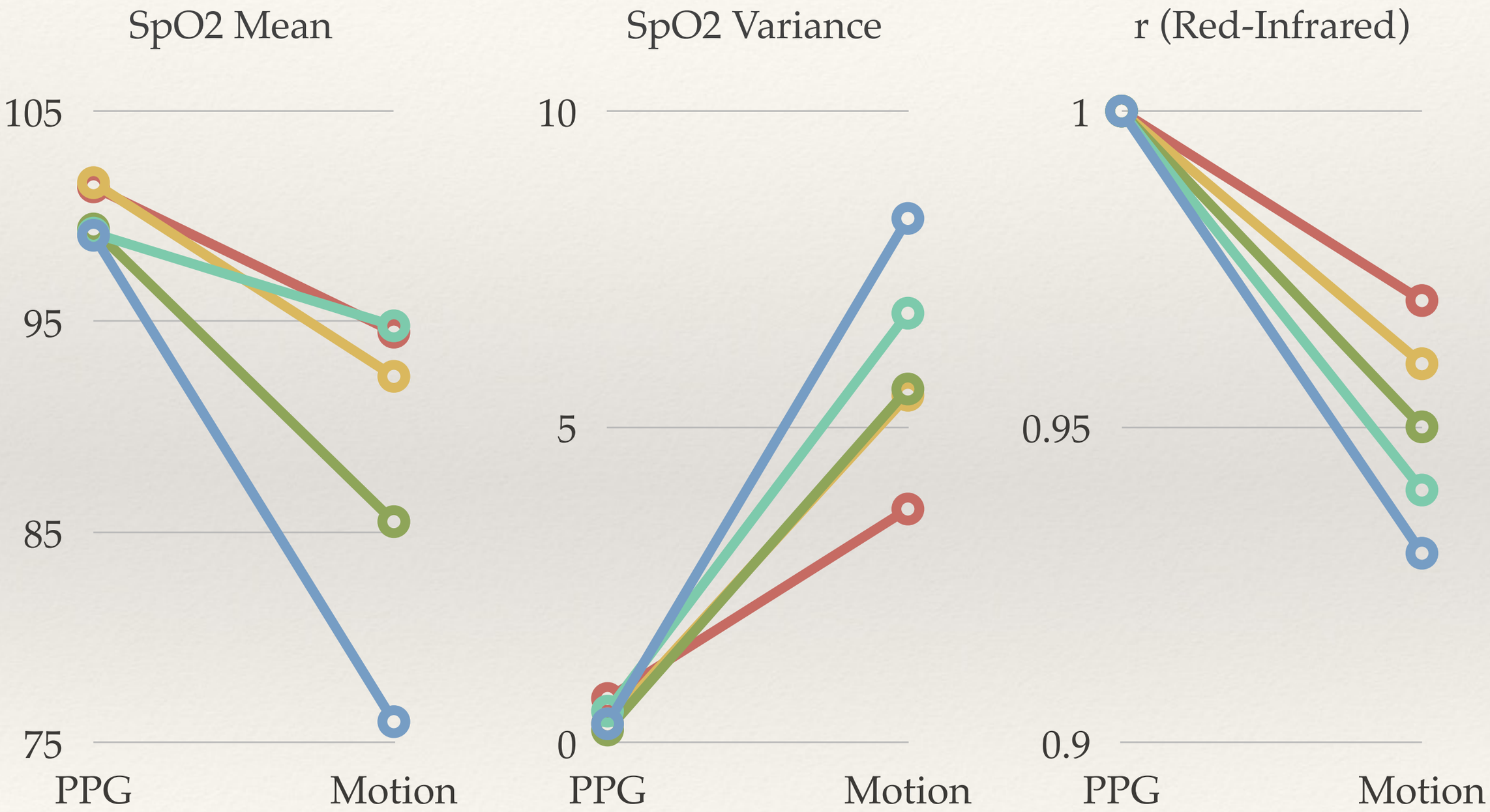
$$R_N = \frac{\varepsilon_{Hb,Red}[Hb] + \varepsilon_{HbO2,Red}[HbO_2]}{\varepsilon_{Hb,IR}[Hb] + \varepsilon_{HbO2,IR}[HbO_2]}$$

Analytical Models

For both models:

- R_N approaches a constant
- Red / infrared correlation decreases

Isolated Motion Artifact



Summary

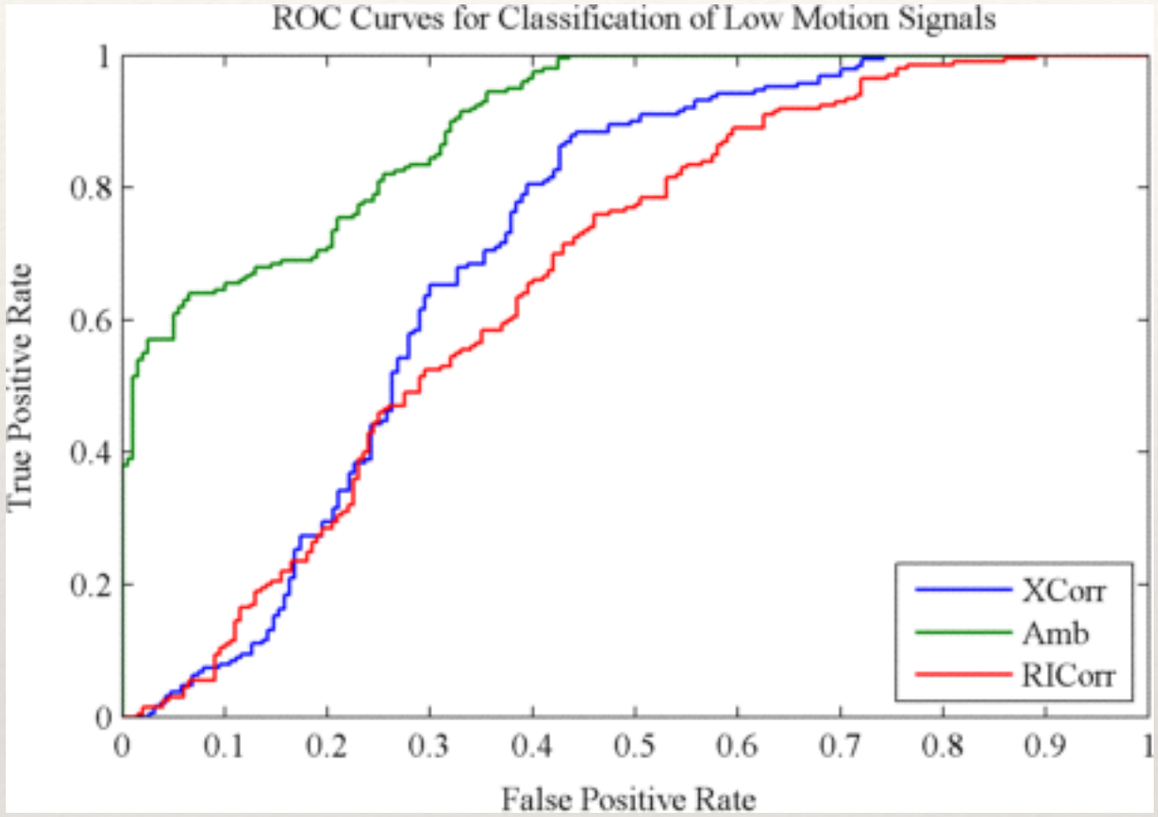
- Isolated motion artifact shows evidence for both proposed motion artifact models
- There is insufficient evidence to distinguish between the effects of the two proposed models

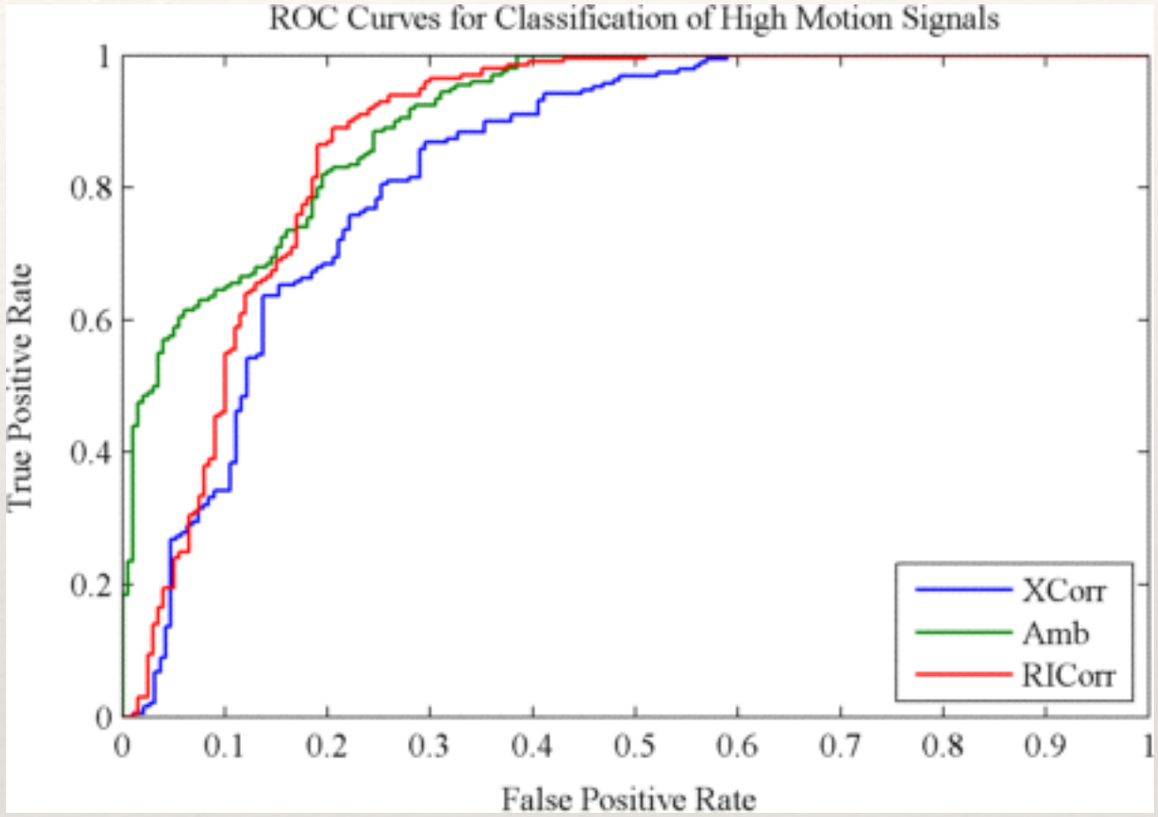
Contribution 3:

Development and evaluation of automatic signal quality assessment

- Propose three SQI algorithms
- Test for ability to detect motion contamination
- Test for correlation with true SNR in artificially contaminated data

Results - Real Data

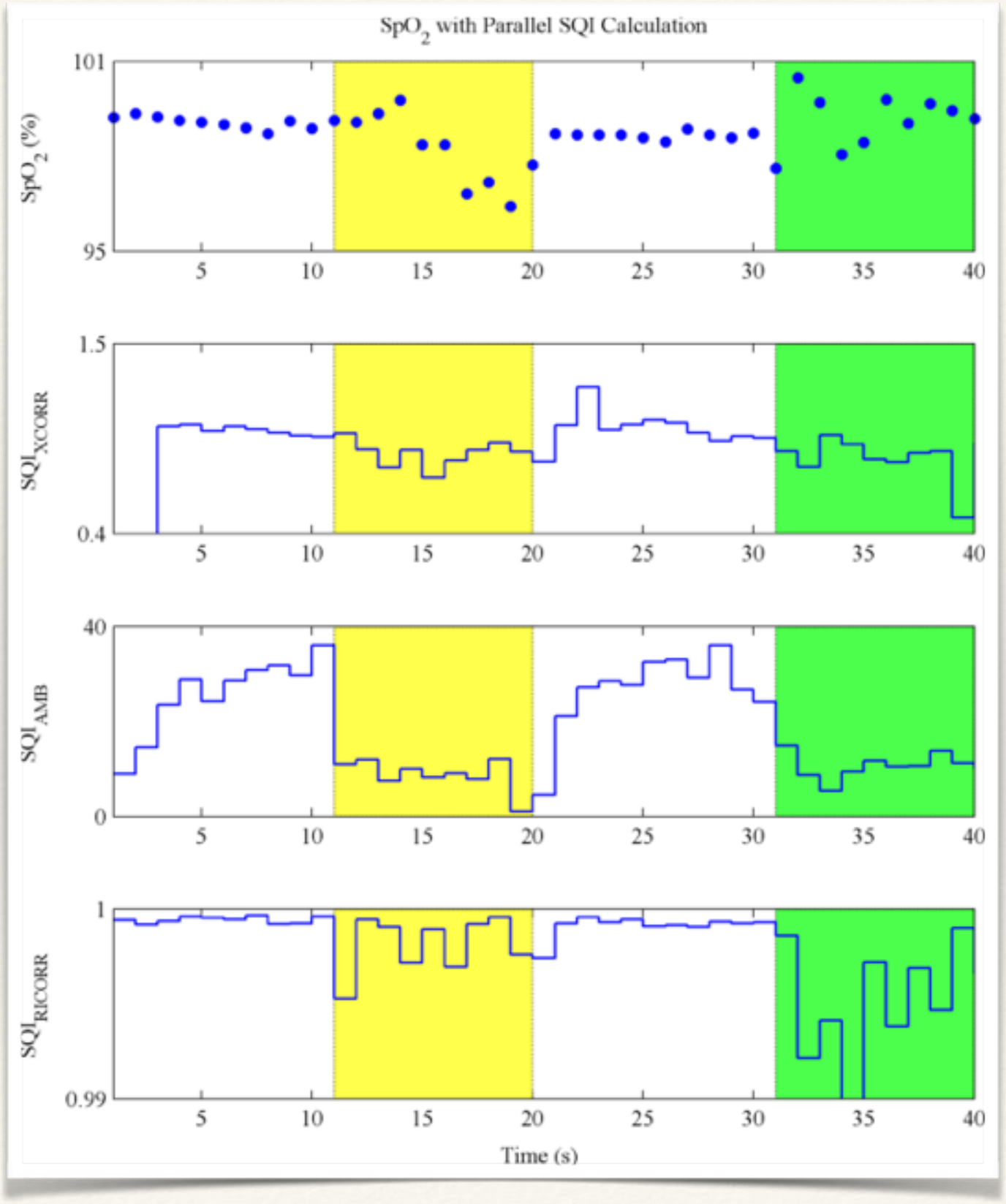




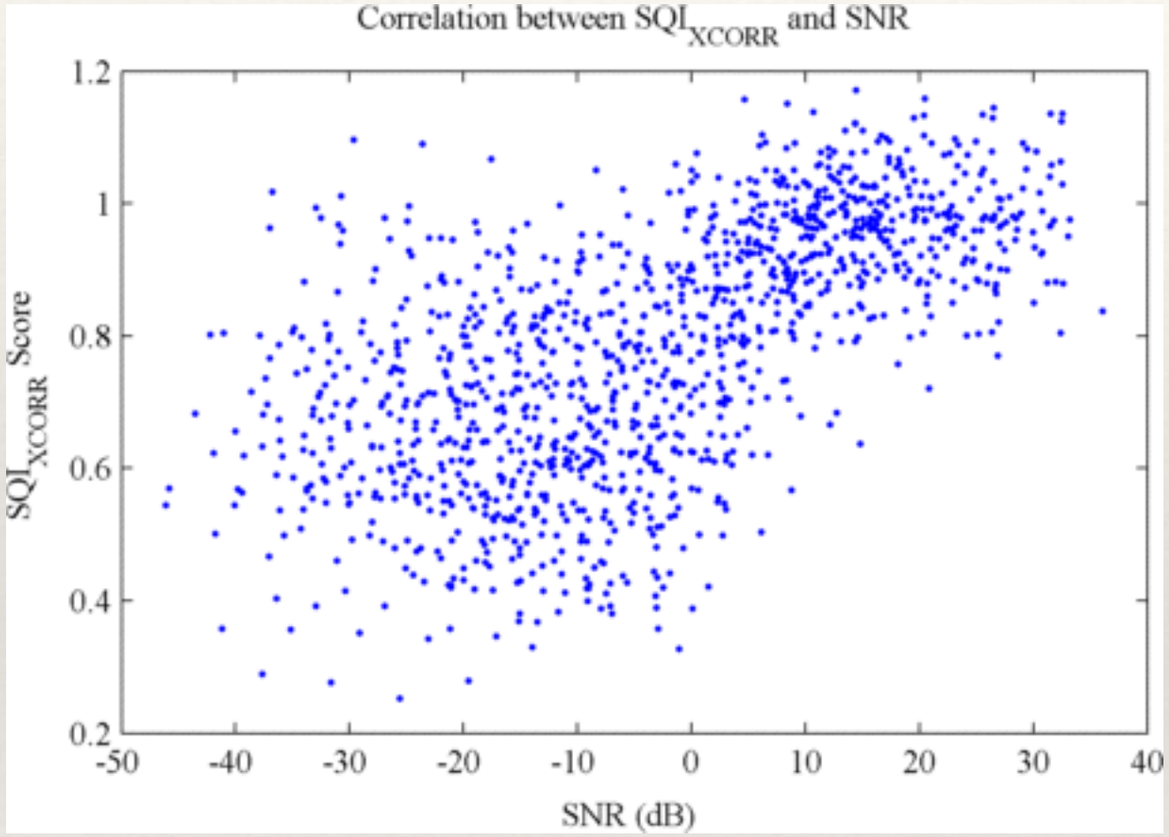
SQI	AUC
XCorr	0.71
Amb	0.90
RICorr	0.67

SQI	AUC
XCorr	0.84
Amb	0.91
RICorr	0.88

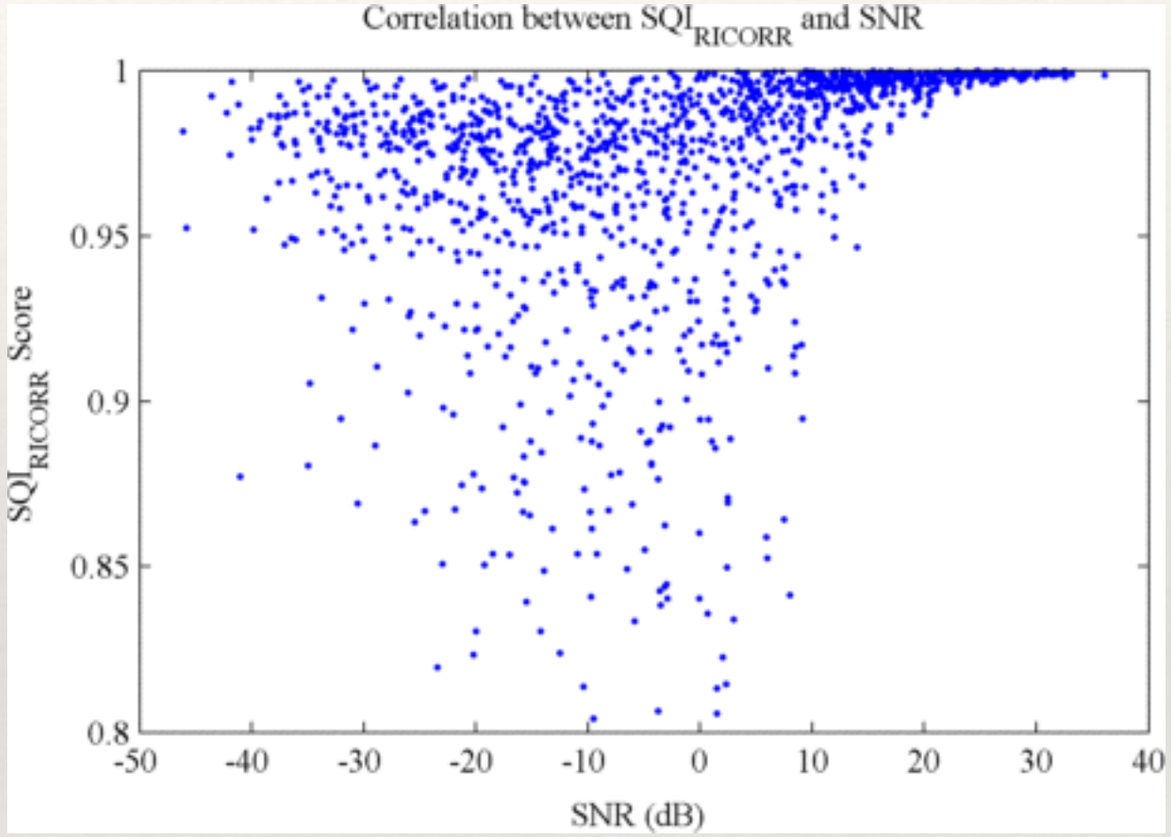
Contribution 3: Development and evaluation of automatic signal quality assessment



Results - Artificially Contaminated Data



$r_S = 0.66$



$r_S = 0.54$

Summary

- All algorithms showed reasonable discrimination between high motion and motionless PPG
- Discrimination performance of XCorr and RICorr decreased for low motion PPG
- XCorr and RICorr show positive monotonic correlation with SNR in artificially contaminated signals

Publications

- "Effects of motion artifact on the blood oxygen saturation estimate in pulse oximetry"
  - 2014 IEEE International Symposium on Medical Measurements and Applications
- "Quantifying Blood-Oxygen Saturation Measurement Error in Motion Contaminated Pulse Oximetry Signals"
  - 2015 World Congress on Medical Physics and Biomedical Engineering (accepted)
- Automatic Signal Quality Assessment in Pulse Oximetry
  - (Journal manuscript in progress)

Future Work

- Evaluating the effects of motion artifact should be repeated with a variety of motion generation protocols
- Analytical models can inform development of hardware-based motion artifact mitigation technique
- Further work on SQI algorithms can determine SQI thresholds for unacceptable SpO2 error

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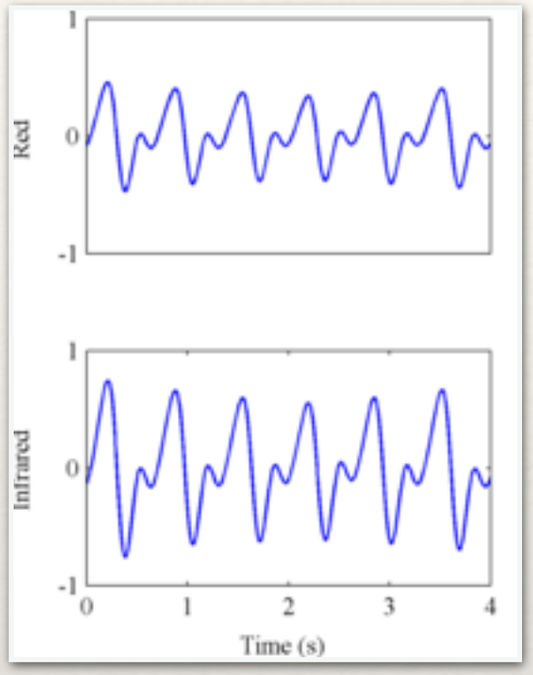
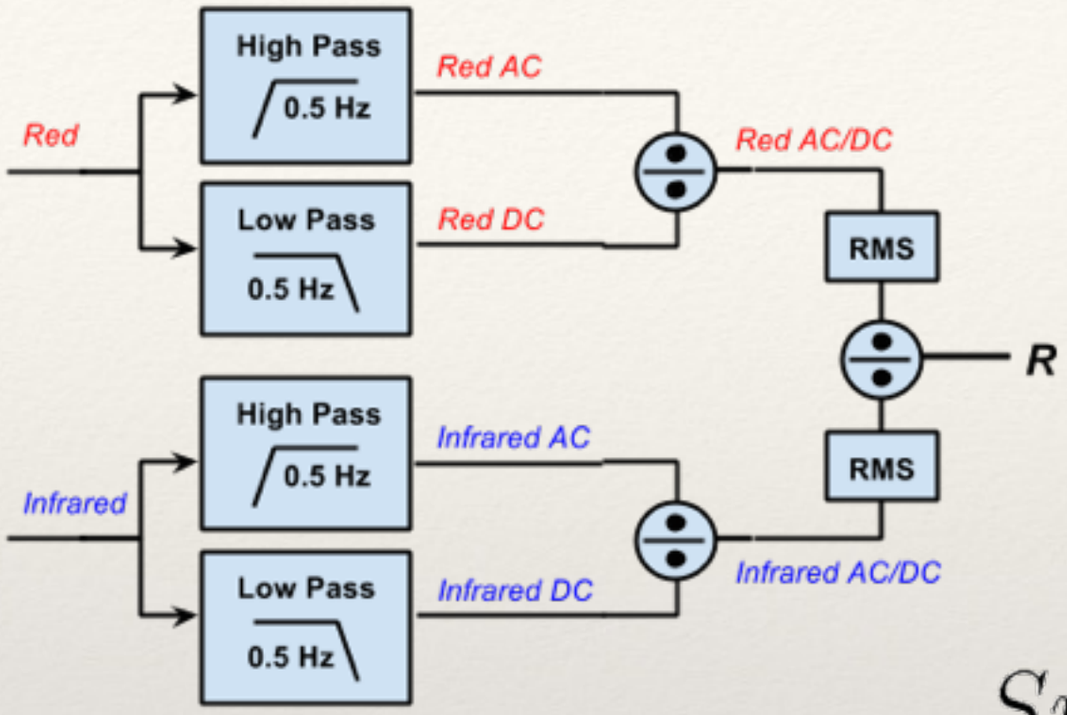
$$R = \frac{AC_{Red}/DC_{Red}}{AC_{IR}/DC_{IR}} = \frac{\varepsilon_{Hb,Red}[Hb] + \varepsilon_{HbO2,Red}[HbO_2]}{\varepsilon_{Hb,IR}[Hb] + \varepsilon_{HbO2,IR}[HbO_2]}$$





$$SpO_2 = a - bR$$

Background

Calculation of R and SpO2

Isolated Motion Artifact

	Control PPG			Isolated Motion Artifact		
	SpO2 ($\bar{x}$)	SpO2 (s)	r	SpO2 ($\bar{x}$)	SpO2 (s)	r
Subject 1	99.1	0.3	1.00	76.0	8.3	0.93
Subject 2	99.2	0.5	1.00	94.8	6.8	0.94
Subject 3	99.4	0.2	1.00	85.5	5.6	0.95
Subject 4	101.6	0.3	1.00	92.4	5.5	0.96
Subject 5	101.4	0.7	1.00	94.5	3.7	0.97