Extraction of respiratory signals from the electrocardiogram and photoplethysmogram: technical and physiological determinants

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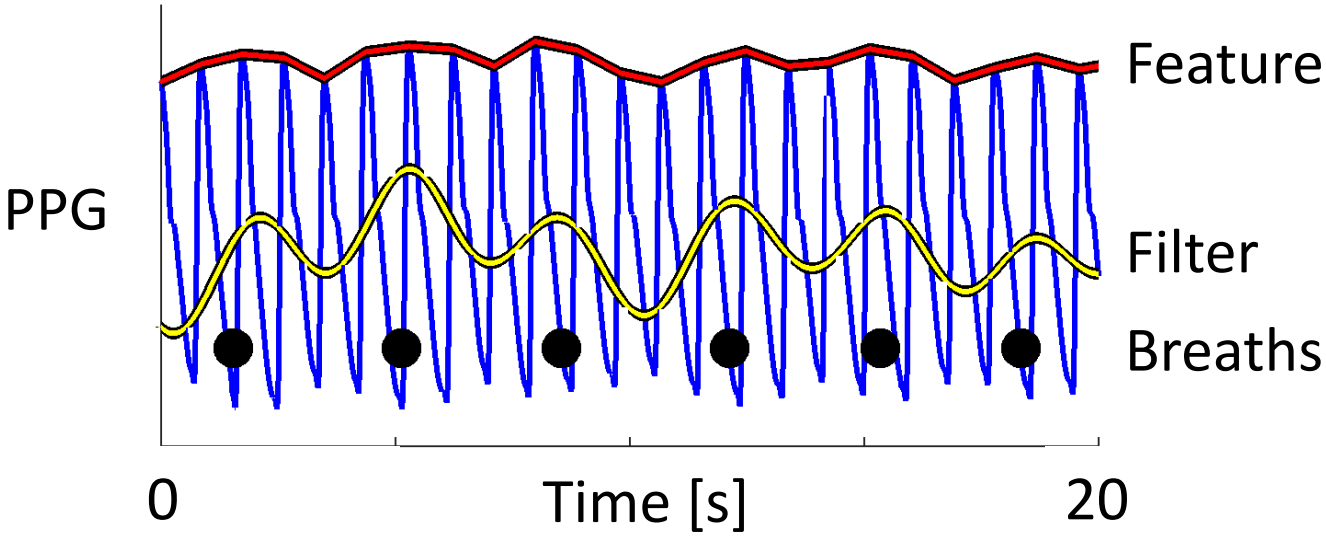
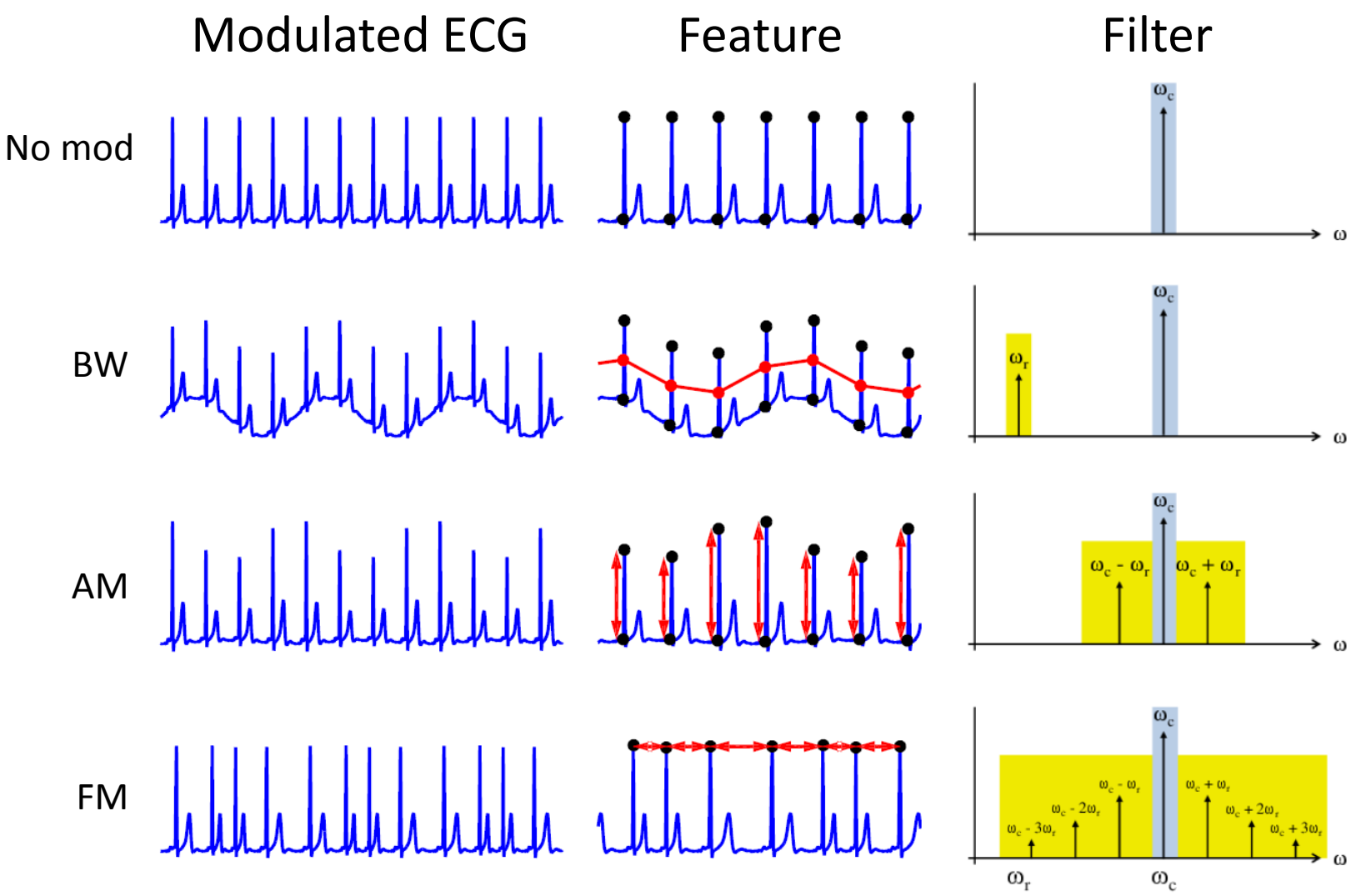
Clinical Need

Respiratory modulations

- Breathing rate (BR) can be estimated from ECG and PPG in young, healthy subjects using laboratory equipment.
- Respiratory modulations must be of sufficient quality
- Several factors may affect quality in clinical setting



Measurement



Factors

Technical	Physiological
PPG measurement site: finger or ear	Age
Signal acquisition equipment: laboratory or clinical	Gender
Input signal: ECG or PPG	Breathing rate (BR)
Sampling frequency	

inform device design

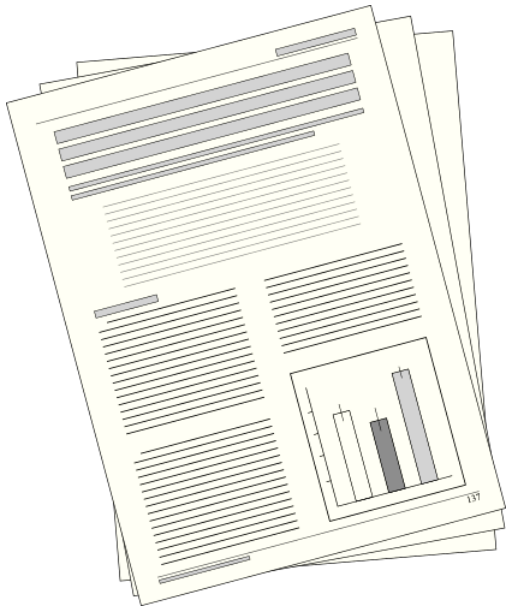
determine clinical acceptability

Aim

Aim

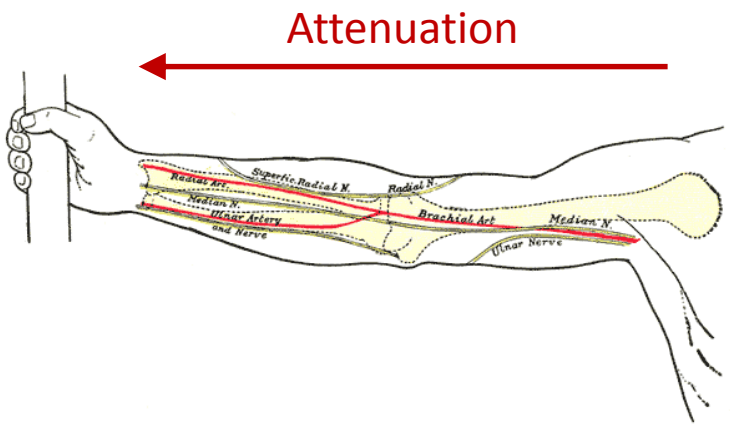
Determine the influences of technical and physiological factors on respiratory modulations

Prior Work



PPG Measurement Site

- **Finger**, **ear**, forearm, shoulder, forehead
- BW greater at ear than finger
- No comparisons of AM and FM



Source: Gray H., Anatomy of the Human Body, 1918

ECG or PPG

- Different physiological mechanisms
- FM greater in PPG
- ECG superior in young, healthy subjects

Modulation	ECG	PPG
BW	Thoracic impedance changes and orientation of heart's electrical axis relative to ECG electrodes	Blood volume changes
AM		Stroke volume changes
FM	Respiratory sinus arrhythmia: HR increases during inhalation and decreases during exhalation	

Equipment Type

- auto-gain, auto-centre, amplitude gain

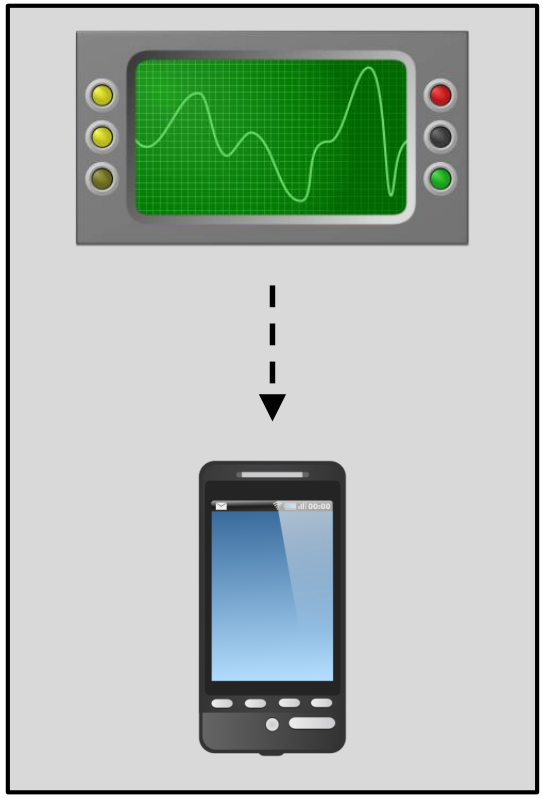
- Our previous study and several others: Laboratory
- MIMIC II: Clinical
- Smart phone PPGs: Lower grade

- AM differs between PPG monitors

Sampling Frequency

higher sampling frequency = higher quality ?

- Several studies up to 1000 Hz
- Our previous study: 500 Hz
- MIMIC II: 125 Hz
- CapnoBase: 100 Hz
- Smart phone PPGs: ~ 30 Hz



Age

- Respiratory sinus arrhythmia and chest wall expansion diminish with age
- FM-based ECG algorithms less accurate in elderly subjects
- No effect on BW-based PPG algorithms

Gender

- Greater FM in PPG in women than men
- BW in PPG not influenced by gender

Respiratory Rate

- Respiratory sinus arrhythmia reduced at increased BR
- AM of PPG reduced at increased BR
- Viscoelasticity may reduce BW of PPG at increased BR
- Elevated BR indicates deterioration

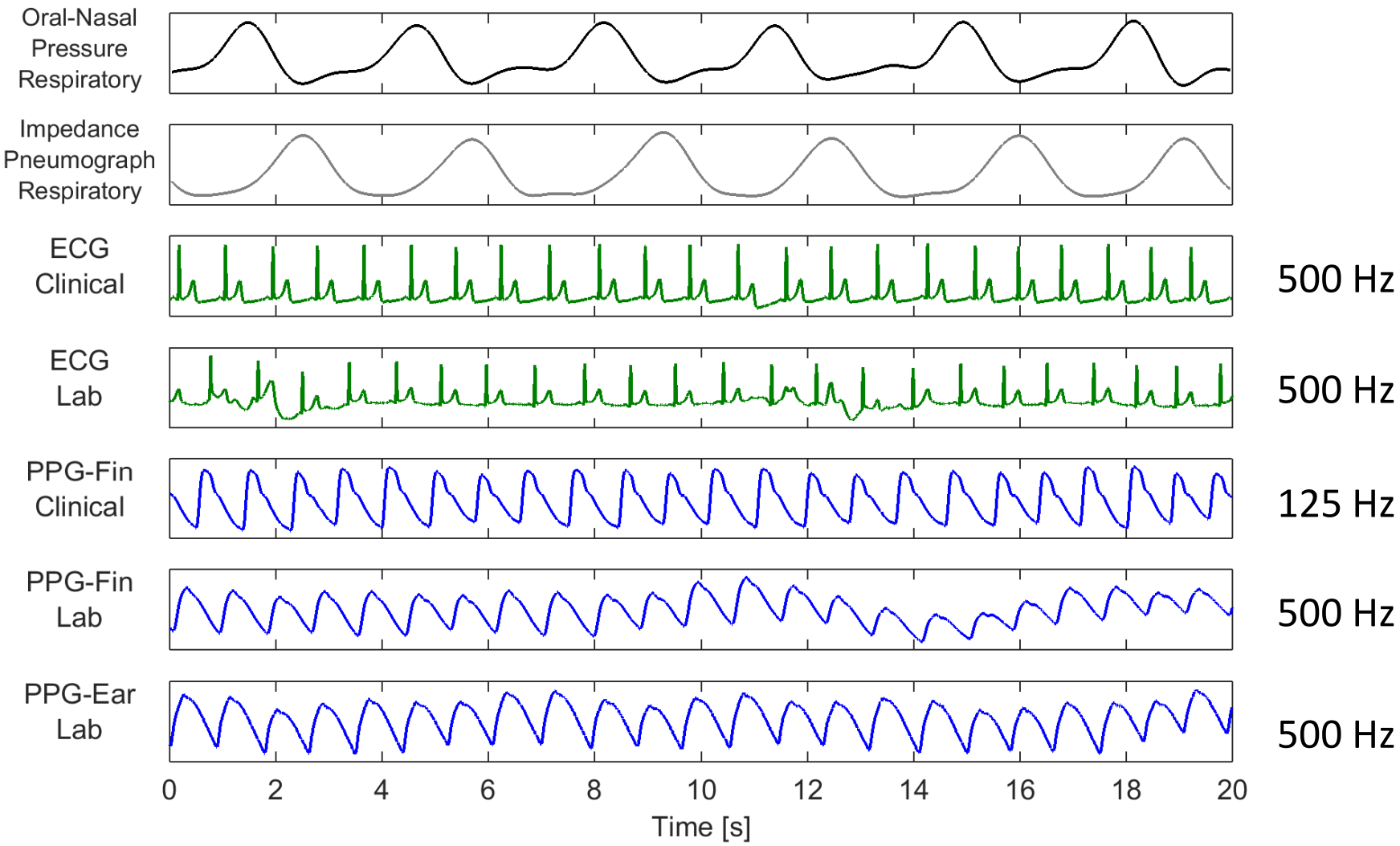
Methods

Participants

- Two cohorts:
  - young (18-40 yrs)
  - elderly (70+)
- Healthy
- Exclusions:
  - Co-morbidities or medications that affect cardiac, respiratory or autonomic nervous systems

National Clinical Trial 01472133

Signals


Oral-Nasal
Pressure
Respiratory
Impedance
Pneumograph
Respiratory
ECG
Clinical
ECG
Lab
PPG-Fin
Clinical
PPG-Fin
Lab
PPG-Ear
Lab
500 Hz
500 Hz
125 Hz
500 Hz
500 Hz
0
2
4
6
8
10
12
14
16
18
20
Time [s]

Signal Processing

- 32 s windows
- Quality assessment (SQIs)
- Extract respiratory modulations

Signal Processing

Filter-based	Feature-based
BW: Band-pass filter	BW: mean amplitude of troughs and proceeding peaks
AM: Continuous Wavelet Transform	AM: Difference between amplitudes of troughs and proceeding peaks
FM: Continuous Wavelet Transform	FM: time interval between consecutive peaks
	BW: mean signal value between consecutive troughs
	BW, AM: peak amplitude
	BW, AM: trough amplitude
	FM: QRS duration
	AM, FM: QRS area
	BW: Principal component analysis
	FM: PPG pulse width
	AM, FM: QR slope
	AM, FM: RS slope
	AM, FM: QRS angle

Signal Processing

- 32 s windows
- Exclude low quality windows using SQIs
- Extract respiratory modulations
- Modulation quality: correlation with oral-nasal pressure

Statistics

- Non-parametric tests
- Correction for multiple comparisons

Results

Dataset

- 58 subjects included

	Young (N = 41)	Elderly (N = 16)
Age [yrs]: med (lq - uq)	29 (26 - 31)	75 (72 - 78)
BMI [kgm^{-2}]: med (lq - uq)	23 (21 - 26)	25 (24 - 26)
Female sex (%)	51	56

- 20 (19 - 20) windows per subject (32 s duration)
- BR: 4 – 33 bpm
- HR : 40 – 100 bpm

PPG Measurement Site

Modulation	Finger vs Ear CCs
X_{A1}	**Finger**
X_{A2}	NS
X_{A3}	NS
X_{B1}	**Finger**
X_{B2}	NS
X_{B3}	**Finger**
X_{B4}	**Finger**
X_{B5}	**Finger**
X_{B6}	**Finger**
X_{B9}	NS
X_{B10}	**Finger**

- Ear signals eliminated

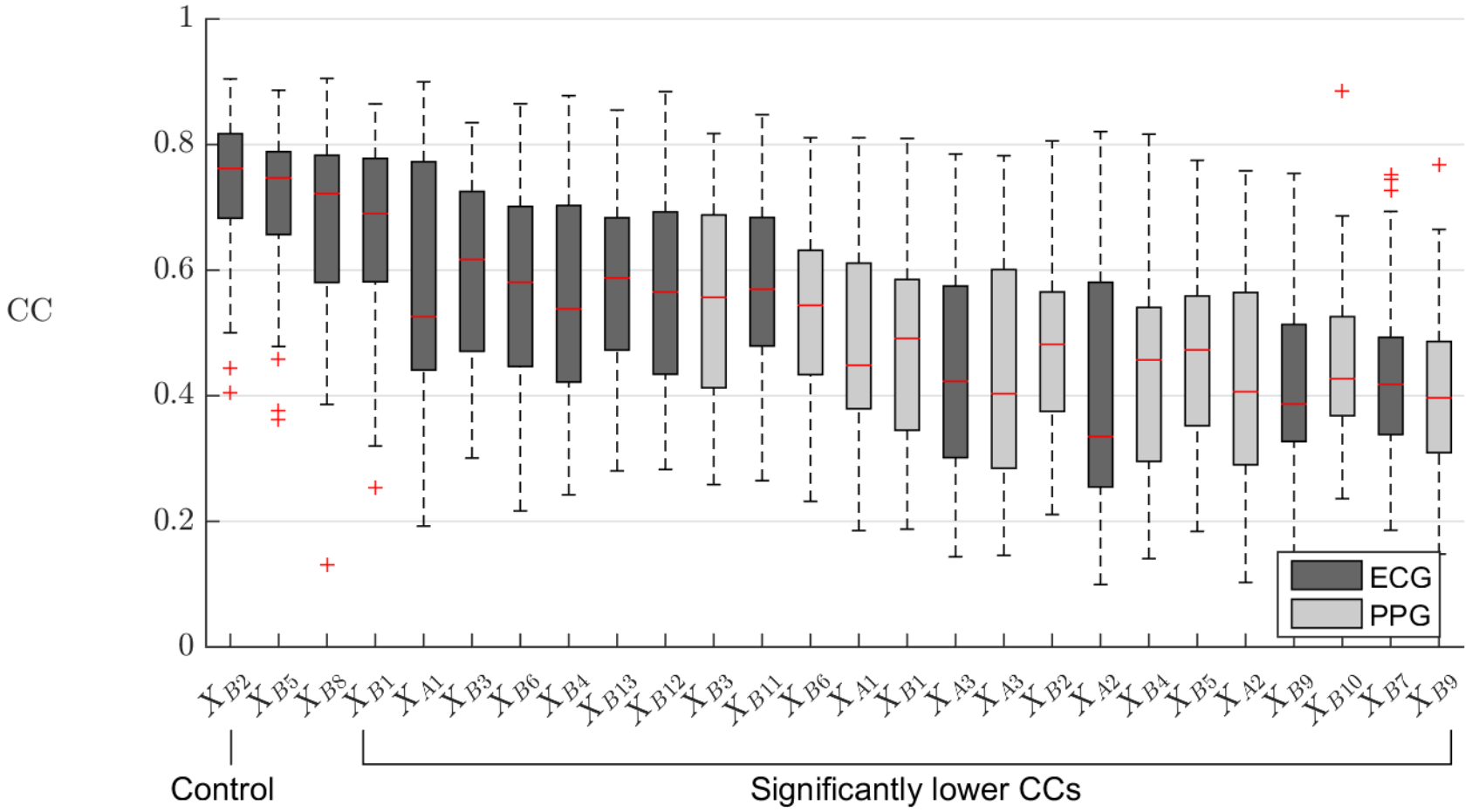
Equipment Type

Modulation	Clinical vs Lab ECG CCs
X_{A1}	NS
X_{A2}	**Clinical**
X_{A3}	NS
X_{B1}	**Clinical**
X_{B2}	NS
X_{B3}	NS
X_{B4}	NS
X_{B5}	**Clinical**
X_{B6}	NS
X_{B7}	NS
X_{B8}	NS
X_{B9}	NS
X_{B11}	NS
X_{B12}	NS
X_{B13}	NS

Modulation	Clinical vs Lab PPG CCs
X_{A1}	**Clinical**
X_{A2}	NS
X_{A3}	**Lab**
X_{B1}	**Clinical**
X_{B2}	**Lab**
X_{B3}	**Clinical**
X_{B4}	NS
X_{B5}	NS
X_{B6}	**Clinical**
X_{B9}	NS
X_{B10}	NS

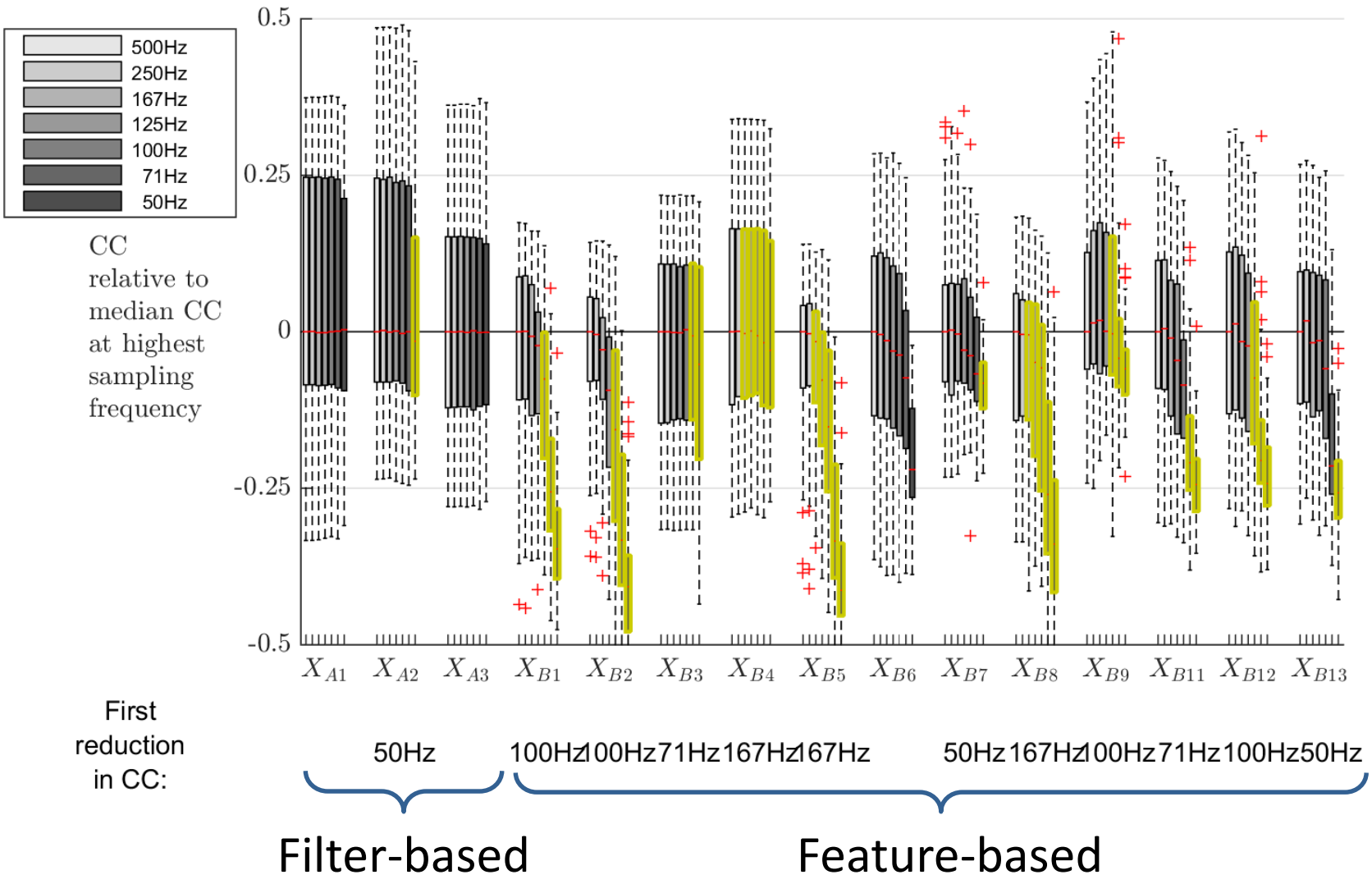
- Clinical signals retained

ECG or PPG

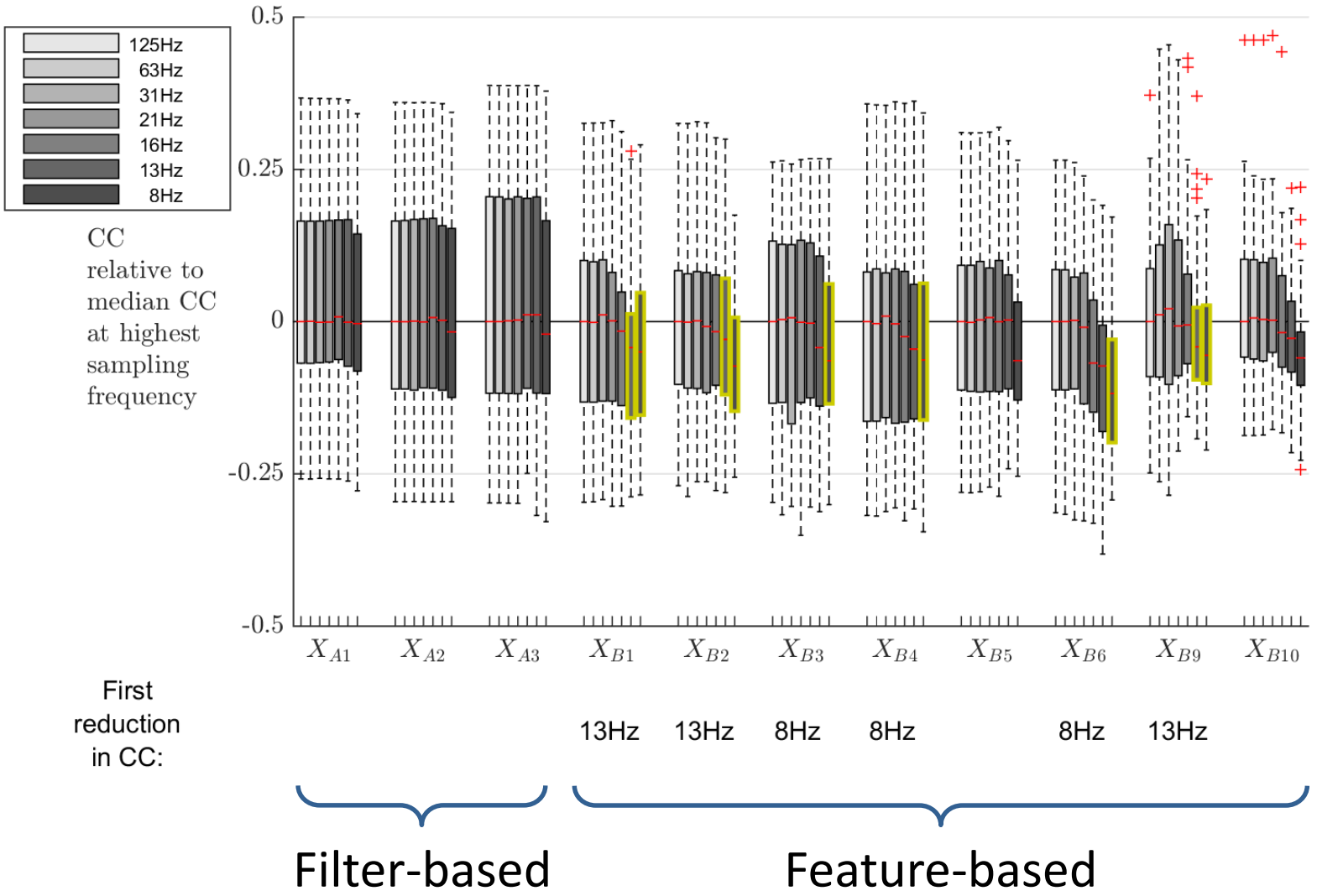


- ECG largely superior

Sampling Frequency: ECG



Sampling Frequency: PPG

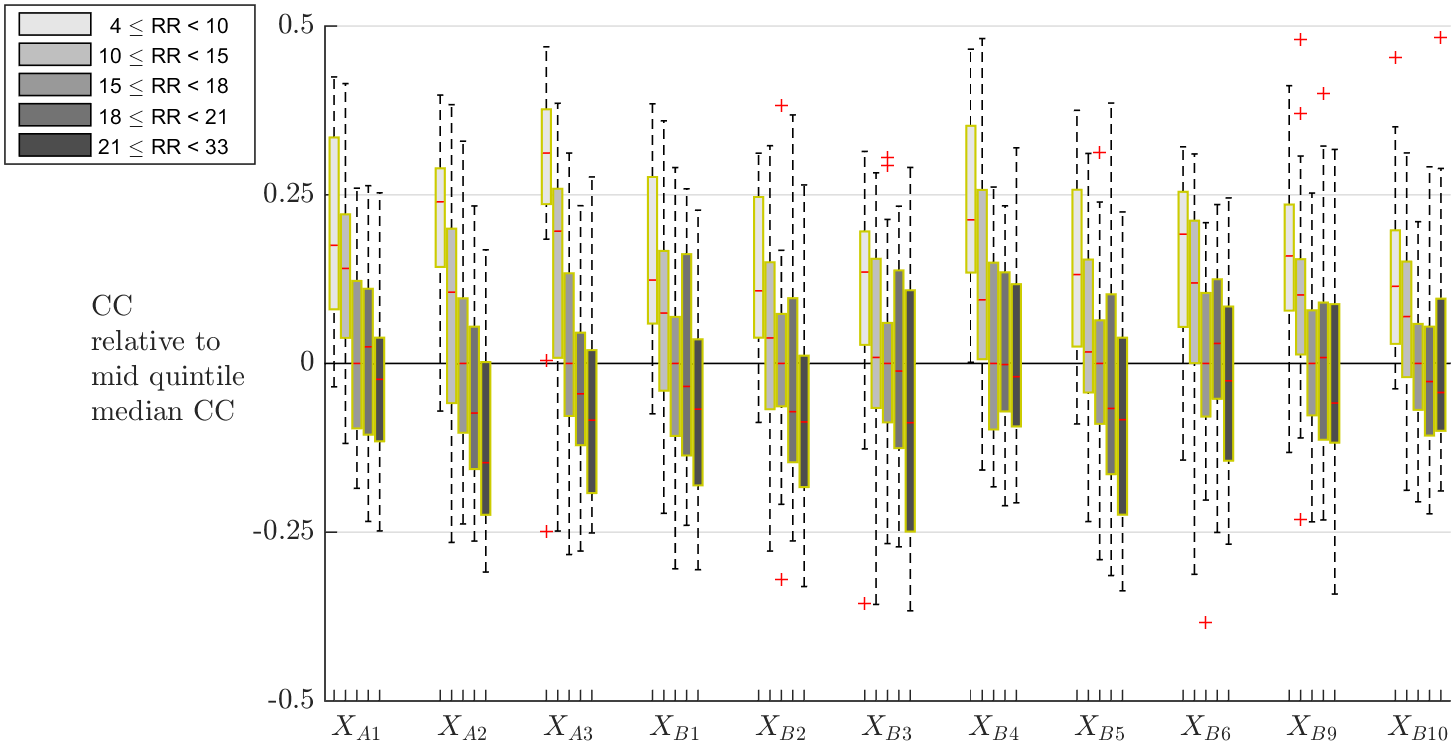


Age and Gender

- FM-based PPG significantly greater in young subjects

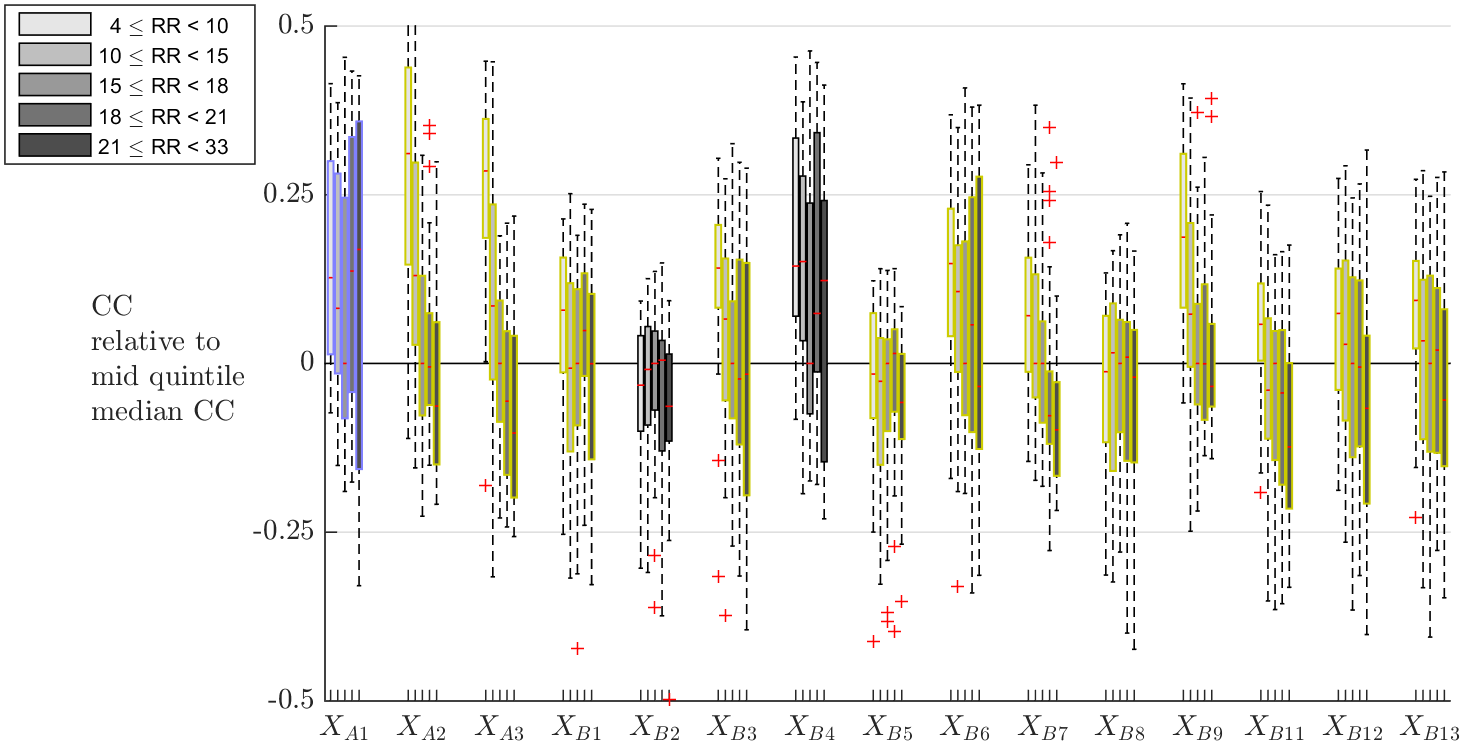
- No differences with gender

Respiratory Rate: PPG



Kendall's rank CC:	X_{A1}	X_{A2}	X_{A3}	X_{B1}	X_{B2}	X_{B3}	X_{B4}	X_{B5}	X_{B6}	X_{B9}	X_{B10}
	-0.31	-0.46	-0.50	-0.30	-0.28	-0.27	-0.36	-0.29	-0.33	-0.27	-0.14

Respiratory Rate: ECG



Discussion

Recommendations

- Device design recommendations:
  - Finger PPG rather than ear,
  - Clinical equipment acceptable, and
  - ECG superior to PPG
  - ECG sampling frequency $\geq$ 250 Hz
  - PPG sampling frequency $\geq$ 16 Hz
- Clinical considerations:
  - FM-based PPG modulation reduced in elderly
  - No differences between men and women
  - Qualities of modulations reduced at higher BRs

Limitations

- Small sample size for elderly (N = 16)
- One laboratory and one clinical monitor
- Cannot extrapolate to other scenarios

Future Work

- Investigate effects of:
  - Clinical population
  - Movement artifact

Conclusions

- Assessed the impact of technical and physiological factors on respiratory modulations extracted from ECG and PPG
- Provided recommendations
- The toolbox of algorithms and the dataset will be made publicly available here

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The views expressed are those of the authors and not necessarily those of the EPSRC, NHS, NIHR, Department of Health, Wellcome Trust, or Royal Academy of Engineering.

References and Resources

This presentation is part of the **Respiratory Rate Estimation Project** at:

http://peterhcharlton.github.io/RRest/

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