Fusion Algorithm for the Detection of ECG Characteristic Points

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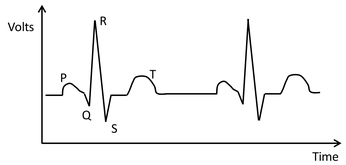
Objective

- The Electrocardiogram (ECG) is a key diagnostic monitor used by clinicians for in-patient and increasingly for Out-patients.
- Temporal location of ECG P, Q, R, S and T phases enables many diagnostic decisions
  - Pulse → from R phase spacing
  - Changes in intervals between waves can be indicators of various conditions or identify risks

Figure 1: Typical ECG signal



- **Challenges**
  - Noise – ECG signals are mV range
  - Normal variations in wave form
    - Inverted T waves
    - Additional phases – Normal conditions, Infants
    - Medical conditions: Missing, extra, variant phases
  - ECGs are non-stationary signals:
    - Vary over time and cycle to cycle
    - Spectrum is very different for the each of the phases
- **Dataset**
  - ECG training set (33 ECGs) from www.physionet.org
    - 26 ECGs: "PTB Diagnostic ECG Database"
    - 4 ECGs: "Non-Invasive Fetal ECG Database"
    - 3 ECGs: "Intracardiac Atrial Fibrillation Database"

Detection Examples

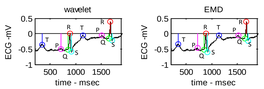


Figure 8: ECG that has significant drift (S0017)

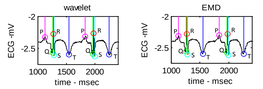


Figure 9: Inverted T wave ECG (S0061)

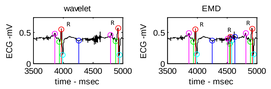


Figure 10: ECG that has a movement artifact at 4500 msec. (S0101) Wavelet : correct; EMD: FP error.

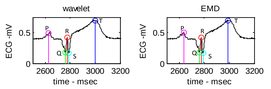


Figure 11: ECG with extremely large T wave relative to QRS complex. (S0036)

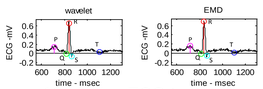


Figure 12: Noisy ECG that has small T wave. (S0026)

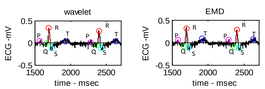


Figure 13: Very noisy ECG (S0035)

Multi-resolution Wavelet analysis

- **Overview:**
  - Decompose signals into frequency bands using short length filters to allow for compact support in time
  - Results in a series of detail and final approximation signals representing various frequency bands of the signal

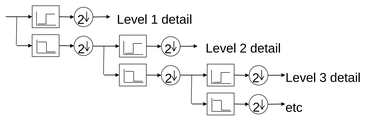


Figure 2: Dyadic wavelet decomposition filter

- **Detection algorithm**

Create reconstructions
WLe1: Detail 4,5,6
WLe2: Detail 6xDetail 4,5
WLe1e2: abs(WLe1*WLe2)
→
Do peak search on WLe1e2
Peak: WLe1e2 > 5% max(WLe1e2)
→ Candidate R phases
→
WLe3: 60Hz IIR LPF of ECG
Take derivatives of WLe1 and WLe3 and correlate
→
True up R phases - Search correlation for local maxima near candidate R phases
→ R phase locations
→
Calculate 5 pt slope of WLe1

For each R phase
Search for preceding minima
→ Q phase
→
For each R phase
Search for following minima
→ S phase
→
Create WLe4 – Approx 5 reconstruction
→
Search for maxima before each Q phase
→ P Phase
→
Measure slope trend post S phase
Update T phase trend measure
Based on trend search for maxima / minima post S phase
→ T Phase

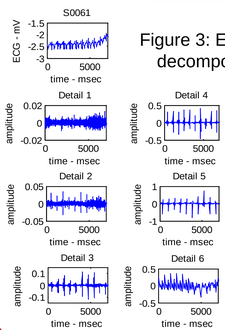


Figure 3: Example ECG wavelet decomposition – R phase in detail 2-5

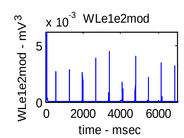
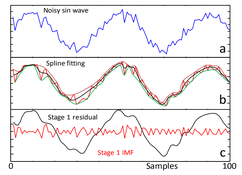


Figure 4: Example correlation signal indicating R waves

Empirical Mode Decomposition

- **Overview**
  - EMD effectively uses the signal itself as the decomposition reference.
  - Decomposes signal into a series of Intrinsic Mode Functions (IMF) and a resulting residue
  - Reconstruction is simple through addition of IMFs and final residual



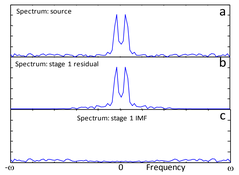


Figure 5: Example EMD decomposition of a noisy sin wave showing resulting first IMF and residual

- **Detection algorithm**

Search IMF set for lowest IMF with short term energy variation
→
EMDe1: Use this IMF + next 5 and build power signal
EMDe3: 60Hx IIR LPF
→
True up R phases using correlation of derivative of EMDe1, EMDe3 (same method as wavelet algorithm)
→ R Phases

Use same method as wavelet using EMDe3 as signal
→ Q phases
→ S Phases
→
EMDe4: 60Hz FIR LPF signal
Search EMDe4 as per wavelet
→ P Phases
→ T phases

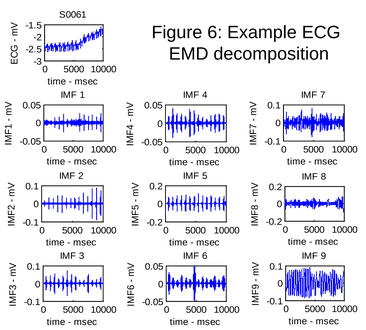


Figure 6: Example ECG EMD decomposition

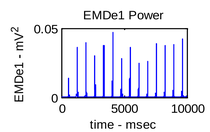


Figure 7: Example EMDe1 power signal indicating R waves

Fusion Detection algorithm

Calculate R phase candidates per EMD and Wavelet algorithms
→ two R phase candidate sets
→
Calculate pulse estimate
→
Find R phase pairs (+/- 20 samples) in sets
→
Processed unpaired R phases
- If adjacent pairs from different algorithm
  → if pulses are close: choose nearest to pulse predicted location
  otherwise treat as separate R phases
→
For separate R phases – Accept if close to predicted pulse location
→
Build final set → R phases
→
Use EMD algorithm → Q & S phases
→
Find EMD and wavelet algorithm P and T phase candidate sets
Use average PQ gap to identify P wave → P phases
Use average ST gap to identify T wave → T phases

Conclusions

- None of the errors are common between the EMD and wavelet algorithms enabling fusion algorithm to be developed with improved performance.
- Low false positive (FP) and false negative (FN) rates with fusion technique with false negative errors rates of less than 1.0% and only 2 false positive errors across almost 1500 phases analyzed
- Wavelet: Shows good rejection of movement artifacts
- P, Q, S, T accuracy highly dependent on the R phase detection accuracy

Future work

- Extend algorithm to support block processing for longer duration ECGs
- Include classification models to enhance detection performance
- Test algorithm on longer (duration) ECGs and on ECGs outside training set

Results

Phase	Total	Detected	Missed	Extra	TP Rate	TP st.dev	FP Rate	FN Rate
P	362	355	7	2	98.1%	0.044	0.55%	1.93%
Q	410	403	7	3	98.3%	0.043	0.73%	1.71%
R	443	436	7	3	98.5%	0.040	0.68%	1.58%
S	411	401	10	2	97.6%	0.060	0.49%	2.43%
T	411	400	11	2	97.3%	0.049	0.49%	2.68%

Table 1: Detection results for wavelet algorithm

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Table 2: Detection results for EMD algorithm

Phase	Total	Detected	Missed	Extra	TP Rate	TP st.dev	FP Rate	FN Rate
P	269	269	0	0	100%	0.000	0.00%	0.00%
Q	302	300	2	0	99.3%	0.039	0.00%	0.66%
R	334	332	2	1	99.4%	0.035	0.30%	0.60%
S	301	298	3	1	98.9%	0.044	0.33%	1.00%
T	302	299	3	0	99.0%	0.033	0.00%	0.99%

Table 3: Detection results for Fusion algorithm