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A RELIABILITY-ORIENTED ENGINEERING FRAMEWORK FOR WEARABLE ECG MONITORING

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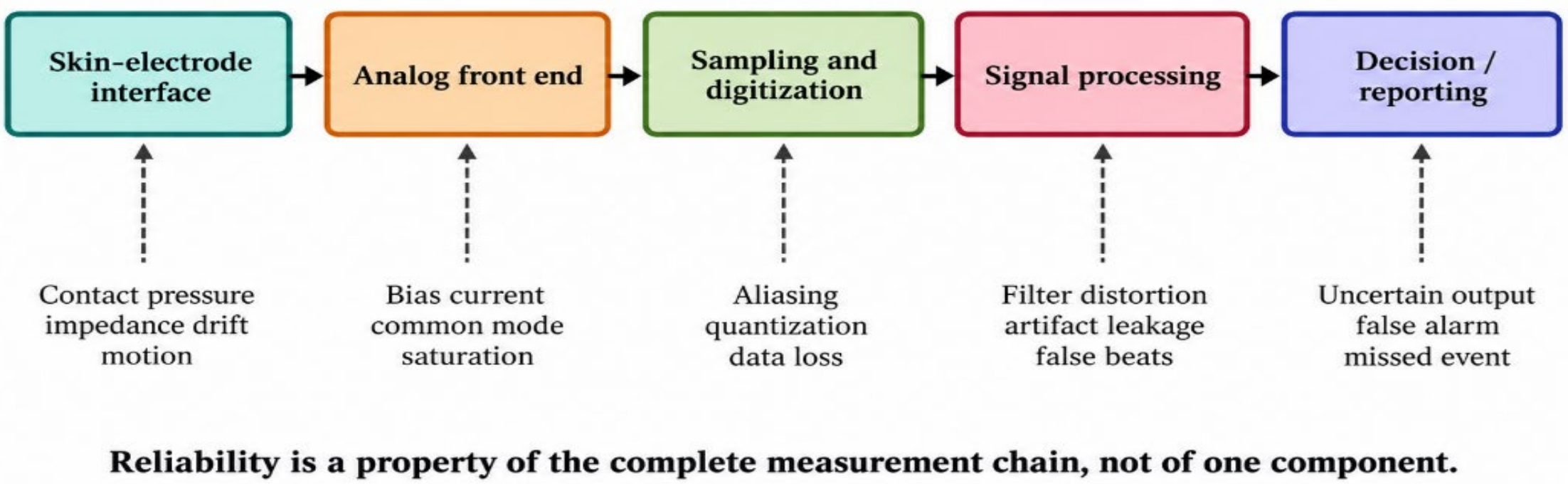
Purpose and Central Argument

- A clean ECG waveform is not, by itself, proof of reliable measurement.
- Errors can originate anywhere from the electrode–skin interface to the final decision.
- The study proposes evidence-gated verification across the complete measurement chain.
- Synthetic filtering results illustrate recoverability—not clinical validity.

Wearable ECG: Reliability Challenges

- Electrode contact varies with motion, pressure, sweat and time.
- Front-end interference, clipping and recovery can distort or erase information.
- Timing gaps, transmission loss and processing may hide acquisition failures.
- Verification should be tied to intended use and known failure modes.

Reliability Is a Measurement-Chain Property



Errors and uncertainties propagate through the full chain; no single component can guarantee reliable ECG.

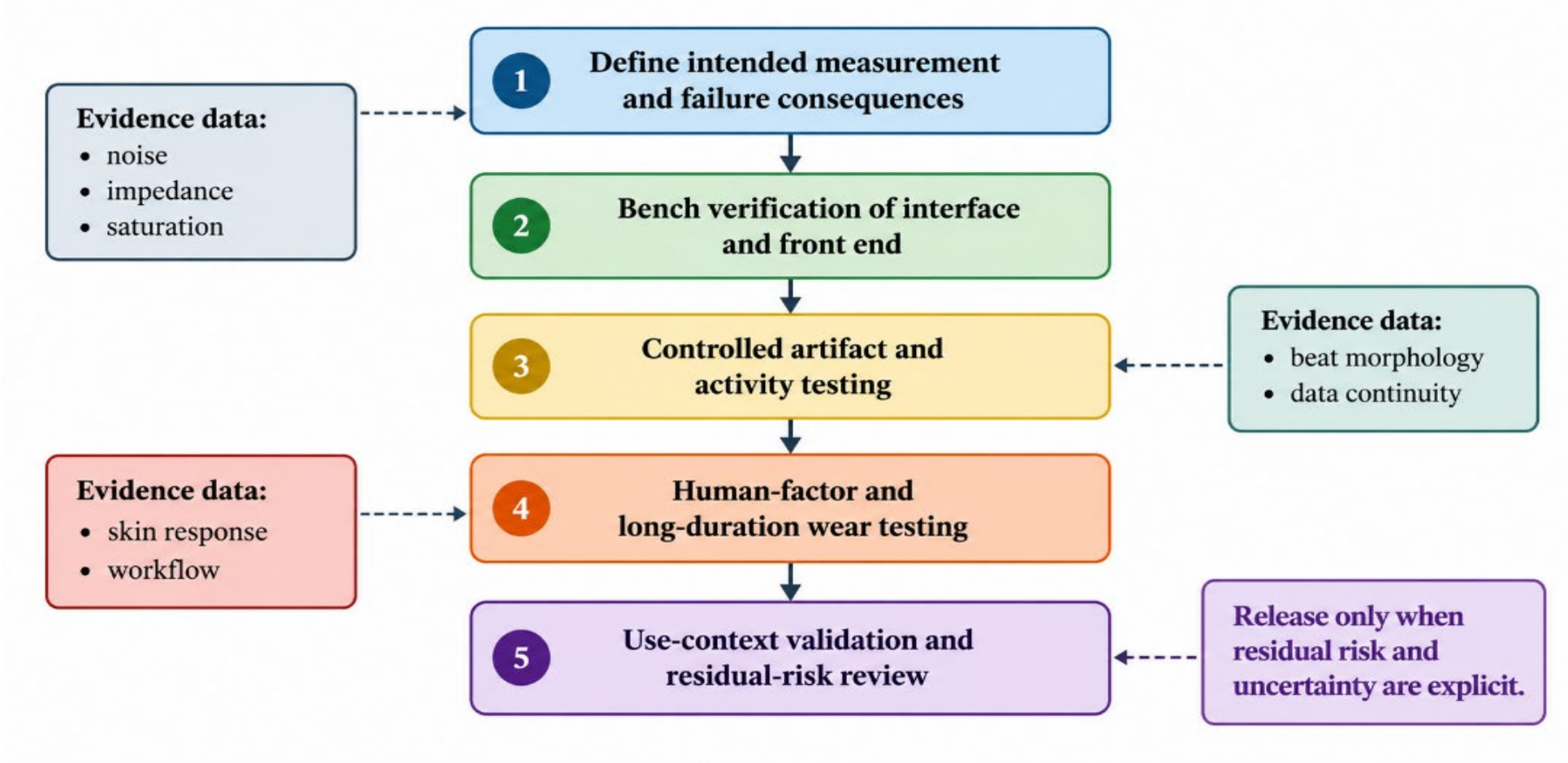
What Must Be Verified?

- Interface: contact impedance, drift and movement sensitivity.
- Acquisition: common-mode rejection, overload and recovery.
- Digitization: timestamps, missed samples and data integrity.
- Processing: both noise reduction and waveform preservation.
- Wear and use context: long-duration function and residual risk.

Failure-Oriented Evidence Map

- Interface drift → impedance versus time, posture and moisture.
- Motion artifacts → synchronized controlled-motion testing.
- Front-end saturation → overload and recovery tests.
- Data discontinuity → timestamp and packet-integrity audit.
- Filtering distortion → reference-morphology comparison.
- Wear failure → long-duration comfort, adhesion and skin checks.

Verification Route: Five Evidence Gates



Definition → electrical bench → controlled artifacts → long-duration wear → use-context validation

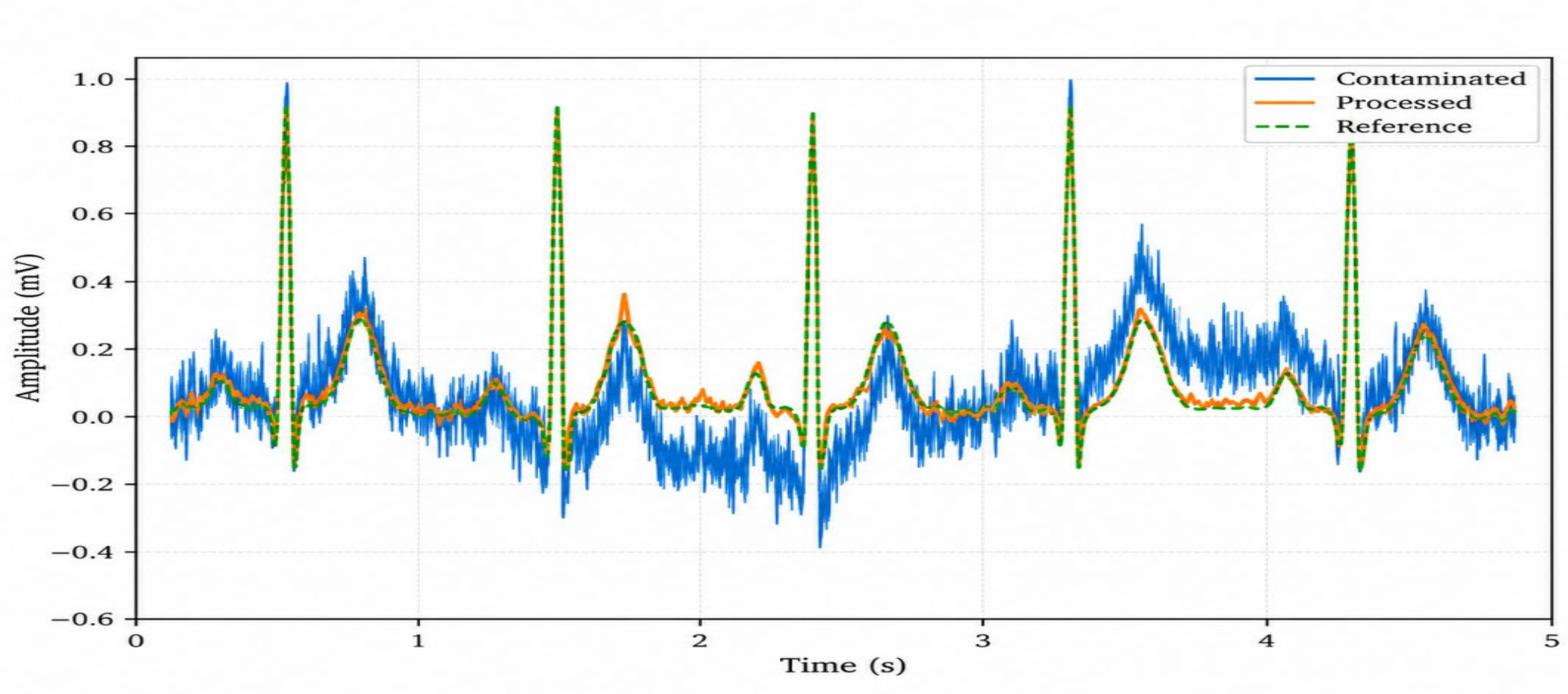
Reliability-Oriented ECG Interval Decision

- Check timestamps, missing data, saturation and electrode contact.
- Assess baseline disturbance, interference and beat plausibility.
- Hard failure → INVALID; caution limits → DEGRADED.
- Only intervals meeting all checks are ACCEPTED.
- Preserve the quality state and failure reason with the signal.

Computational Case Study: Design

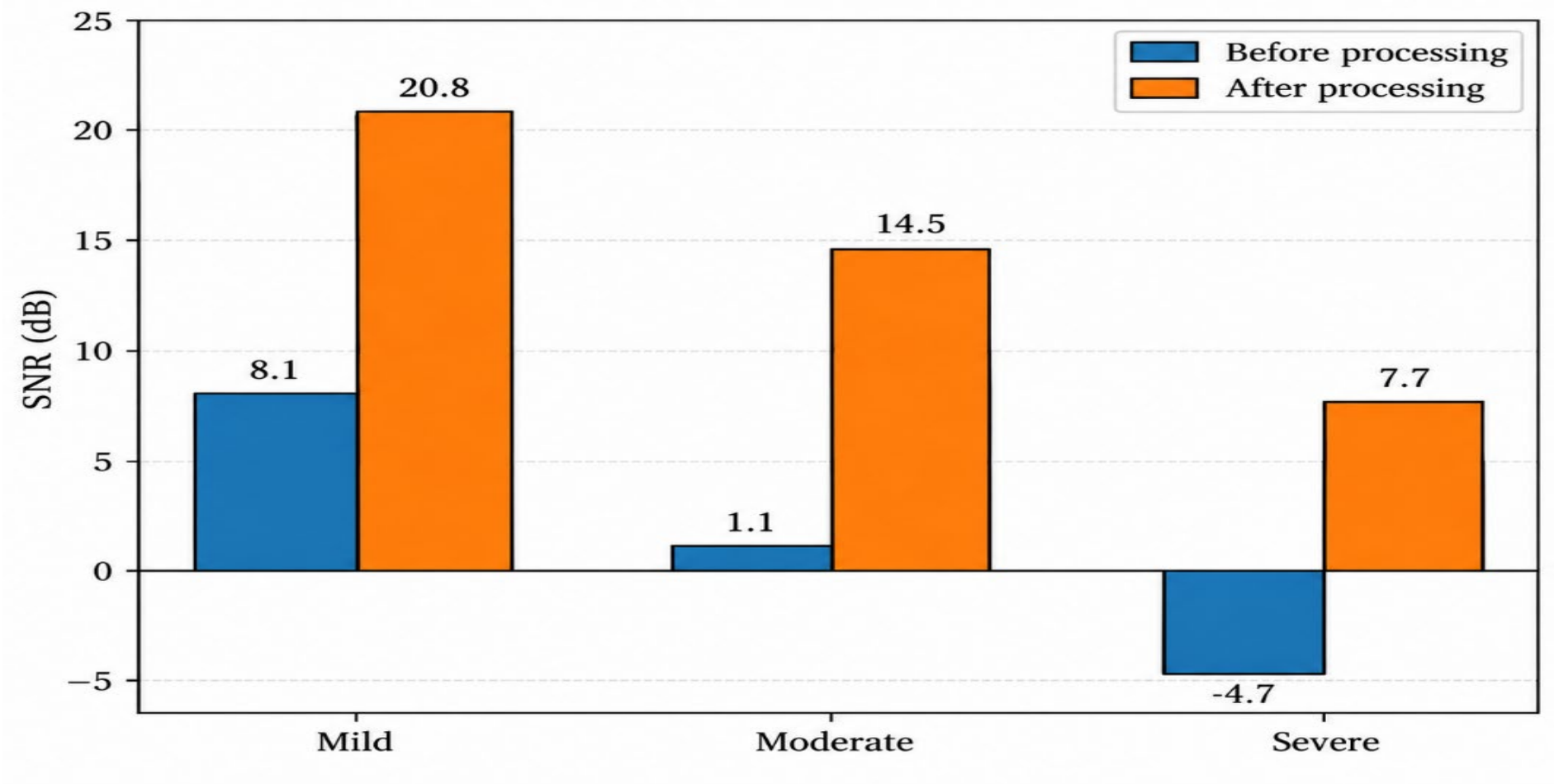
- 20 s synthetic ECG at 500 Hz; one beat per second.
- Mild, moderate and severe artifact conditions with fixed random seed 13.
- Artifacts include baseline wander (0.33 Hz), 50 Hz interference, noise and motion-like transients.
- Offline 0.5–40 Hz Butterworth band-pass + 50 Hz notch filtering.
- Comparisons assess SNR, RMSE and QRS-peak bias.

Representative ECG: Before and After Filtering



Moderate-artifact case: filtering visibly improves the waveform, but cannot reveal data that was never acquired.

SNR Improvement Across Artifact Levels



Reported SNR gains: mild +12.71 dB | moderate +13.35 dB | severe +12.35 dB

Quantitative Results: Synthetic Signals

Case	SNR before → after (dB)	RMSE before → after (mV)	QRS bias before → after
Mild	8.11 → 20.82	0.0657 → 0.0152	4.38% → 0.13%
Moderate	1.13 → 14.49	0.1467 → 0.0315	9.01% → 0.65%
Severe	−4.65 → 7.70	0.2855 → 0.0689	20.15% → −0.17%

RMSE decreases by 75.87–78.51% under these defined synthetic conditions.

What the Numerical Case Does—and Does Not—Show

- It demonstrates offline recovery from modeled additive artifacts.
- The filtering implementation uses forward–backward zero-phase processing.
- It does not test electrode detachment, amplifier clipping or missing packets.
- The synthetic findings are not clinical or long-duration device validation.

Engineering Design Implications

- Make lead-off, saturation, contact quality and timestamp continuity observable.
- Label uncertain intervals rather than silently reporting clean values.
- Balance signal quality against comfort, adhesion, skin effects and energy use.
- Link each claimed performance benefit to an appropriate verification level.

Research Directions

- Report electrode behavior as distributions and long-duration trajectories.
- Use synchronized movement references when studying motion artifacts.
- Include acquisition-state metadata in shared wearable-ECG datasets.
- Distinguish algorithm robustness from physical measurement reliability.
- Develop traceable failure-to-test-to-acceptance maps for specific device classes.

Conclusions

- Wearable ECG reliability must be verified end to end.
- Signal processing can substantially improve synthetic waveform quality.
- A visibly clean trace does not establish acquisition integrity or intended-use validity.
- Evidence gates and explicit residual uncertainty support defensible technical release decisions.