

Supplementary Information for:

A real-time infrastructure transforming HRV streams into inference-ready, context-aware data objects for digital biomarker development

Supplementary Table S1. Backend-generated JSON data object schema for inference-ready HRV export

field name	object level	data type	requiredness	availability	description	unit	inference_readiness_role
session_metadata.session_id	session metadata	string	required	always available for the containing object	Unique identifier of the exported recording session.		export provenance
session_metadata.subject_id	session metadata	string_or_null	conditional	available in subject-linked or multi-subject export mode	Subject identifier linking physiology to the correct participant stream.		subject-level linkage
session_metadata.session_started_at	session metadata	string	required	always available for the containing object	ISO 8601 timestamp of session initiation.		export provenance
session_metadata.active_phase	session metadata	string	required	always available for the containing object	Phase active when the export object was created.		phase-aware segmentation
raw_rr_data_reference_or_raw_data_if_available	raw-data linkage	mixed	required, nullable	included available when raw RR data or a raw-data reference is included	Embedded raw RR data or reference to the corresponding raw-data resource.		reproducibility metadata
computed_hrv_windows	computed HRV window	array_or_empty	required	always available; empty until relevant records exist	Ordered collection of backend-generated rolling HRV state objects.		downstream model input
computed_hrv_windows[] timestamp	computed HRV window	float	required	always available for the containing object	Timestamp assigned by the backend to the source sample.	s	temporal alignment
computed_hrv_windows[] elapsedSec	computed HRV window	float	required	always available for the containing object	Elapsed processing time assigned to the source sample.	s	temporal alignment
computed_hrv_windows[] rRms	computed HRV window	float	required	always available for the containing object	Most recent RR interval received by the processing engine.	ms	downstream model input
computed_hrv_windows[] heartRate	computed HRV window	float_or_null	required, nullable	available after sufficient rolling window data	Rolling heart-rate estimate derived from accepted NN intervals.	beats/min	downstream model input
computed_hrv_windows[] rRmsd	computed HRV window	float_or_null	required, nullable	available after sufficient rolling window data	Rolling root mean square of eligible successive NN interval differences.	ms	downstream model input
computed_hrv_windows[] sdnn	computed HRV window	float_or_null	required, nullable	available after sufficient rolling window data	Sample standard deviation of accepted NN intervals in the rolling window.	ms	downstream model input
computed_hrv_windows[] sdnnDetrended	computed HRV window	float_or_null	required, nullable	available after sufficient rolling window data	SDNN after removal of a linear trend from the rolling NN series.	ms	downstream model input
computed_hrv_windows[] pnn50	computed HRV window	float_or_null	required, nullable	available after sufficient rolling window data	Percentage of eligible successive NN differences greater than 50 ms.	%	downstream model input
computed_hrv_windows[] baevskyI	computed HRV window	float_or_null	required, nullable	available after sufficient rolling window data	Experimental Baevsky stress-index calculation from the recent NN distribution.	arbitrary units	downstream model input
computed_hrv_windows[] hPower	computed HRV window	float_or_null	conditional	available only when PSD readiness criteria are met	High-frequency RR spectral power integrated over 0.04–0.15 Hz.	ms ²	downstream model input
computed_hrv_windows[] hPowerRatio	computed HRV window	float_or_null	conditional	available only when PSD readiness criteria are met	Ratio of low-frequency to non-zero high-frequency RR spectral power.	ratio	downstream model input
computed_hrv_windows[] sHRRatio	computed HRV window	float_or_null	conditional	available after baseline initialization and sufficient PSD readiness	Experimental baseline-referenced transform of log U/F _{HF} ; not a clinical autonomic-balance measure.	0-100	downstream model input
computed_hrv_windows[] autonomicBalanceIndex	computed HRV window	float_or_null	conditional	available only when PSD readiness criteria are met	Dominant RR-oscillation frequency used as an indirect respiration proxy; respiration is not measured.	Hz	downstream model input
computed_hrv_windows[] respirationProxHz	computed HRV window	float_or_null	conditional	available only when PSD readiness criteria are met	Peak-contrast confidence assigned to the RR-derived respiration proxy.	0-1	downstream model input
computed_hrv_windows[] respirationProxConfidence	computed HRV window	float_or_null	conditional	available only when PSD readiness criteria are met	Quality gate combining spectral-window fit and stationarity.	0-1	spectral-readiness gating
computed_hrv_windows[] pnn50Readiness	computed HRV window	float	required	always available for the containing object	Trend-based stationarity component used for spectral-readiness gating.	0-1	spectral-readiness gating
computed_hrv_windows[] pnn50Stationarity	computed HRV window	float	required	always available for the containing object	Fraction of recent RR inputs rejected by the online artifact detector.	proportion	signal-quality filtering
computed_hrv_windows[] artifactRatio	computed HRV window	float	required	always available for the containing object	Signal-quality estimate derived from artifact burden, beat density, and data freshness.	0-1	signal-quality filtering
computed_hrv_windows[] signalConfidence	computed HRV window	float	deprecated_or_legacy	legacy experimental field; retained for compatibility only	Legacy experimental field; not a validated clinical stress score and not used for diagnostic interpretation.	0-100	legacy compatibility only
computed_hrv_windows[] stressScore	computed HRV window	float_or_null	conditional	available after baseline initialization and when recovery logic is evaluable	Experimental engineering readout of post-event state; not a validated clinical recovery score.	0-100	downstream model input
computed_hrv_windows[] recoveryScore	computed HRV window	float_or_null	conditional	available after sufficient signal or completed summary context	Experimental backend state label for interface display; not a diagnostic or prognostic classification.		legacy compatibility only
computed_hrv_windows[] physiologicalState	computed HRV window	string_or_null	deprecated_or_legacy	always available; empty until relevant records exist	Ordered collection of HRV windows enriched with event and phase context.		phase-aware segmentation
annotated_hrv_windows	annotated HRV window	array_or_empty	required	always available for the containing object	Unique identifier of the annotated HRV window.		context-preserving export
annotated_hrv_windows[] window_id	annotated HRV window	string	required	always available for the containing object	ISO 8601 timestamp marking the start of the HRV window.		context-preserving export
annotated_hrv_windows[] window_start_timestamp_iso	annotated HRV window	string	required	always available for the containing object	ISO 8601 timestamp marking the end of the HRV window.		temporal alignment
annotated_hrv_windows[] window_end_timestamp_iso	annotated HRV window	string	required	always available for the containing object	Elapsed session time at the start of the HRV window.	s	temporal alignment
annotated_hrv_windows[] elapsed_session_time_end_s	annotated HRV window	float	required	always available for the containing object	Elapsed session time at the end of the HRV window.	s	temporal alignment
annotated_hrv_windows[] phase_label	annotated HRV window	string	required	available while a user-defined event is active	Phase label assigned by the event annotation layer.		event synchronization
annotated_hrv_windows[] event_active_id	annotated HRV window	string_or_null	required, nullable	populated while a user-defined event is active	Identifier of the event active at the window endpoint.		event synchronization
annotated_hrv_windows[] time_since_phase_start_s	annotated HRV window	float_or_null	required, nullable	populated when the window has an assigned active phase	Time elapsed since onset of the assigned phase.	s	phase-aware segmentation
annotated_hrv_windows[] rRmsd_ms	annotated HRV window	float_or_null	required, nullable	available after sufficient rolling window data	RMSSD value copied into the context-annotated window.	ms	context-preserving export
annotated_hrv_windows[] sdnn_ms	annotated HRV window	float_or_null	required, nullable	available after sufficient rolling window data	SDNN value copied into the context-annotated window.	ms	context-preserving export
annotated_hrv_windows[] pnn50_percent	annotated HRV window	float_or_null	required, nullable	available after sufficient rolling window data	pNN50 value copied into the context-annotated window.	%	context-preserving export
annotated_hrv_windows[] source_sample_rRms	annotated HRV window	float_or_null	required, nullable	available after sufficient rolling window data	Rolling heart-rate value copied into the context-annotated window.	beats/min	context-preserving export
annotated_hrv_windows[] signal_reliability_score	annotated HRV window	float	required	always available for the containing object	Signal-confidence value retained for quality-aware downstream filtering.	0-1	signal-quality filtering
annotated_hrv_windows[] artifact_rate_percent	annotated HRV window	float	required	always available for the containing object	Recent rejected RR proportion expressed as a percentage.	0-1	signal-quality filtering
annotated_hrv_windows[] and_readiness_score	annotated HRV window	float	required	always available for the containing object	Spectral-readiness score retained with the annotated window.	0-1	context-preserving export
annotated_hrv_windows[] source_sample_timestamp	annotated HRV window	float	required	always available for the containing object	Timestamp assigned by the backend to the source sample.	s	temporal alignment
annotated_hrv_windows[] source_sample_elapsedSec	annotated HRV window	float	required	always available for the containing object	Elapsed processing time assigned to the source sample.	s	temporal alignment
annotated_hrv_windows[] source_sample_rRms	annotated HRV window	float	required	always available for the containing object	Most recent RR interval received by the processing engine.	ms	dashboard-to-export traceability
annotated_hrv_windows[] source_sample_hRms	annotated HRV window	float_or_null	required, nullable	available after sufficient rolling window data	Rolling heart-rate estimate derived from accepted NN intervals.	beats/min	dashboard-to-export traceability
annotated_hrv_windows[] source_sample_rRmsd	annotated HRV window	float_or_null	required, nullable	available after sufficient rolling window data	Rolling root mean square of eligible successive NN-interval differences.	ms	dashboard-to-export traceability
annotated_hrv_windows[] source_sample_sdnn	annotated HRV window	float_or_null	required, nullable	available after sufficient rolling window data	Sample standard deviation of accepted NN intervals in the rolling window.	ms	dashboard-to-export traceability
annotated_hrv_windows[] source_sample_sdnnDetrended	annotated HRV window	float_or_null	required, nullable	available after sufficient rolling window data	SDNN after removal of a linear trend from the rolling NN series.	ms	dashboard-to-export traceability
annotated_hrv_windows[] source_sample_pnn50	annotated HRV window	float_or_null	required, nullable	available after sufficient rolling window data	Percentage of eligible successive NN differences greater than 50 ms.	%	dashboard-to-export traceability
annotated_hrv_windows[] source_sample_baevskyI	annotated HRV window	float_or_null	required, nullable	available after sufficient rolling window data	Experimental Baevsky stress-index calculation from the recent NN distribution.	arbitrary units	dashboard-to-export traceability
annotated_hrv_windows[] source_sample_hPower	annotated HRV window	float_or_null	conditional	available only when PSD readiness criteria are met	High-frequency RR spectral power integrated over 0.04–0.15 Hz.	ms ²	dashboard-to-export traceability
annotated_hrv_windows[] source_sample_hPowerRatio	annotated HRV window	float_or_null	conditional	available only when PSD readiness criteria are met	Ratio of low-frequency to non-zero high-frequency RR spectral power.	ratio	dashboard-to-export traceability
annotated_hrv_windows[] source_sample_autonomicBalanceIndex	annotated HRV window	float_or_null	conditional	available after baseline initialization and sufficient PSD readiness	Experimental baseline-referenced transform of log U/F _{HF} ; not a clinical autonomic-balance measure.	0-100	dashboard-to-export traceability
annotated_hrv_windows[] source_sample_respirationProxHz	annotated HRV window	float_or_null	conditional	available only when PSD readiness criteria are met	Dominant RR-oscillation frequency used as an indirect respiration proxy; respiration is not measured.	Hz	dashboard-to-export traceability
annotated_hrv_windows[] source_sample_respirationProxConfidence	annotated HRV window	float	required	always available for the containing object	Peak-contrast confidence assigned to the RR-derived respiration proxy.	0-1	dashboard-to-export traceability
annotated_hrv_windows[] source_sample_pnn50Readiness	annotated HRV window	float	required	always available for the containing object	Quality gate combining spectral-window fit and stationarity.	0-1	spectral-readiness gating
annotated_hrv_windows[] source_sample_pnn50Stationarity	annotated HRV window	float	required	always available for the containing object	Trend-based stationarity component used for spectral-readiness gating.	0-1	spectral-readiness gating
annotated_hrv_windows[] source_sample_artifactRatio	annotated HRV window	float	required	always available for the containing object	Fraction of recent RR inputs rejected by the online artifact detector.	proportion	signal-quality filtering
annotated_hrv_windows[] source_sample_signalConfidence	annotated HRV window	float	required	always available for the containing object	Signal-quality estimate derived from artifact burden, beat density, and data freshness.	0-1	signal-quality filtering
annotated_hrv_windows[] source_sample_stressScore	annotated HRV window	float_or_null	deprecated_or_legacy	legacy experimental field; retained for compatibility only	Legacy experimental field; not a validated clinical stress score and not used for diagnostic interpretation.	0-100	dashboard-to-export traceability
annotated_hrv_windows[] source_sample_recoveryScore	annotated HRV window	float_or_null	conditional	available after baseline initialization and when recovery logic is evaluable	Experimental engineering readout of post-event state; not a validated clinical recovery score.	0-100	dashboard-to-export traceability
annotated_hrv_windows[] source_sample_physiologicalState	annotated HRV window	string_or_null	deprecated_or_legacy	available after sufficient signal or completed summary context	Experimental backend state label for interface display; not a diagnostic or prognostic classification.		dashboard-to-export traceability
session_events	session event	array_or_empty	required	always available; empty until relevant records exist	Chronological collection of user-defined session events and phase boundaries.		event synchronization
session_events[] event_id	session event	string	required	always available for the containing object	Unique identifier of the session event.		event synchronization
session_events[] event_type	session event	string	required	always available for the containing object	Physio-readable event category.		event synchronization
session_events[] event_label	session event	string	required	always available for the containing object	Human-readable event label.		event synchronization
session_events[] phase	session event	string	required	always available for the containing object	Phase associated with the event.		event synchronization
session_events[] action	session event	string	required	always available for the containing object	Event action, such as start, stop, or manual annotation.		event synchronization
session_events[] elapsed_session_time_s	session event	float	required	always available for the containing object	Elapsed session time at event creation.	s	temporal alignment
session_events[] timestamp_iso	session event	mixed	optional	availability depends on export mode and containing object	ISO 8601 event timestamp.		temporal alignment
session_events[] optional_user_note	session event	string_or_null	optional	available only if supplied by the user	Optional free-text annotation entered by the user.		event synchronization
baseline_summary.baseline_start_time	baseline summary	string	required	always available for the containing object	ISO 8601 timestamp of the baseline-segment onset.		baseline-relative modeling
baseline_summary.baseline_end_time	baseline summary	string	required	always available for the containing object	ISO 8601 timestamp of the baseline-segment end.		baseline-relative modeling
baseline_summary.baseline_duration_s	baseline summary	float_or_null	conditional	available after completion of a valid baseline segment	Duration of the completed baseline segment.	s	baseline-relative modeling
baseline_summary.number_of_windows_used	baseline summary	integer	required	available after completed baseline or event segment	Number of valid HRV windows contributing to the baseline summary.	count	baseline-relative modeling
baseline_summary.baseline_stability_label	baseline summary	string_or_null	conditional	available after sufficient signal or completed summary context	Engineering interpretability label derived from baseline signal quality.		baseline-relative modeling
baseline_summary.baseline_rRmsd_mean	baseline summary	float_or_null	conditional	available after completion of a valid baseline segment	Mean RMSSD across baseline windows.	ms	baseline-relative modeling
baseline_summary.baseline_sdnn_mean	baseline summary	float_or_null	conditional	available after completion of a valid baseline segment	Sample standard deviation of RMSSD across baseline windows.	ms	baseline-relative modeling
baseline_summary.baseline_pnn50_mean	baseline summary	float_or_null	conditional	available after completion of a valid baseline segment	Mean SDNN across baseline windows.	%	baseline-relative modeling
baseline_summary.baseline_rRmsd_sd	baseline summary	float_or_null	conditional	available after completion of a valid baseline segment	Sample standard deviation of SDNN across baseline windows.	ms	baseline-relative modeling
baseline_summary.baseline_sdnn_sd	baseline summary	float_or_null	conditional	available after completion of a valid baseline segment	Mean pNN50 across baseline windows.	%	baseline-relative modeling
baseline_summary.baseline_pnn50_sd	baseline summary	float_or_null	conditional	available after completion of a valid baseline segment	Sample standard deviation of pNN50 across baseline windows.	%	baseline-relative modeling
baseline_summary.baseline_hRms_mean	baseline summary	float_or_null	conditional	available after completion of a valid baseline segment	Mean heart rate across baseline windows.	beats/min	baseline-relative modeling
baseline_summary.baseline_hRms_sd	baseline summary	float_or_null	conditional	available after completion of a valid baseline segment	Sample standard deviation of heart rate across baseline windows.	beats/min	baseline-relative modeling
baseline_summary.baseline_signal_reliability_mean	baseline summary	float_or_null	conditional	available after completion of a valid baseline segment	Mean signal-confidence score across baseline windows.	0-1	baseline-relative modeling
baseline_summary.baseline_artifact_rate_mean	baseline summary	float_or_null	conditional	available after completion of a valid baseline segment	Mean artifact rate across baseline windows.	%	baseline-relative modeling
baseline_summary.baseline_artifact_rate_sd	baseline summary	float_or_null	conditional	available after baseline initialization	Baseline-derived metric bounds used for baseline-relative comparison.	%	baseline-relative modeling
baseline_summary.baseline_artifact_rate_mean	baseline summary	float_or_null	conditional	available after baseline initialization	Baseline-derived metric bounds used for baseline-relative comparison.	%	baseline-relative modeling
segment_summaries	segment summary	array_or_empty	required	always available; empty until relevant records exist	Collection of summaries generated for completed annotated segments.		segment-level aggregation
segment_summaries[] segment_id	segment summary	string	required	always available for the containing object	Unique identifier of the completed phase segment.		segment-level aggregation
segment_summaries[] segment_type	segment summary	string	required	always available for the containing object	Type of completed segment represented by the summary.		segment-level aggregation
segment_summaries[] phase_label	segment summary	string	required	always available for the containing object	Phase label assigned to the summarized segment.		phase-aware segmentation
segment_summaries[] start_event_id	segment summary	string	required	always available for the containing object	Identifier of the event that opened the segment.		event synchronization
segment_summaries[] stop_event_id	segment summary	string	required	always available for the containing object	Identifier of the event that closed the segment.		event synchronization
segment_summaries[] duration_s	segment summary	float	required	always available for the containing object	Elapsed duration of the completed segment.	s	temporal alignment
segment_summaries[] number_of_windows_used	segment summary	integer	required	available after completed baseline or event segment	Number of annotated HRV windows included in the segment summary.	count	segment-level aggregation
segment_summaries[] mean_rRmsd	segment summary	float_or_null	conditional	available after completion of the corresponding event segment	Mean RMSSD across windows in the segment.	ms	segment-level aggregation
segment_summaries[] mean_rRms	segment summary	float_or_null	conditional	available after completion of the corresponding event segment	Mean heart rate across windows in the segment.	beats/min	segment-level aggregation
segment_summaries[] mean_sdnn	segment summary	float_or_null	conditional	available after completion of the corresponding event segment	Mean SDNN across windows in the segment.	ms	segment-level aggregation
segment_summaries[] mean_pnn50	segment summary	float_or_null	conditional	available after completion of the corresponding event segment	Mean pNN50 across windows in the segment.	%	segment-level aggregation
segment_summaries[] mean_signal_reliability	segment summary	float_or_null	conditional	available after completion of the corresponding event segment	Mean signal-confidence score across windows in the segment.	0-1	signal-quality filtering
segment_summaries[] mean_artifact_rate	segment summary	float_or_null	conditional	available after completion of the corresponding event segment	Mean artifact rate across windows in the segment.	%	signal-quality filtering
segment_summaries[] interpretability_label	segment summary	string_or_null	conditional	available after sufficient signal or completed summary context	Engineering label indicating whether segment-level readouts are interpretable.		signal-quality filtering
dashboard_readouts	dashboard readout	array_or_empty	optional	available when dashboard readouts are generated	Optional presentation-layer readouts retained for dashboard-to-export traceability.		dashboard-to-export traceability
export_created_at	export	string	required	always available for the containing object	ISO 8601 timestamp at which the export object was serialized.		export provenance

Note: Requiredness and availability refer to the backend-generated export schema. Composite physiological readouts are experimental engineering descriptors and are not validated clinical diagnostic, prognostic, stress, recovery, or decision-support scores.

Supplementary Table S2. Long-format CSV data dictionary for inference-ready HRV window export

variable_name	data_level	data_type	requiredness	availability	description		unit	inference_readiness_role
session_id	HRV window	string	required	available for every exported HRV window	Unique identifier linking the window to its recording session.			session-level linkage
subject_id	HRV window	string	required	available for every exported HRV window	Pseudonymized or system-generated identifier linking the window to the correct subject/session stream; not a directly identifying personal identifier.			subject-level linkage
acquisition_source	HRV window	categorical_string	required	available for every exported HRV window	Acquisition route associated with the physiological stream, such as Polar H10 BLE, ESP32/AD8232 serial acquisition, or synthetic RR replay.			acquisition-source linkage
sensor_id	HRV window	string_or_null	required_nullable	populated when a non-identifying sensor identifier is available	Non-identifying identifier of the acquisition sensor or source.			acquisition-source linkage
window_id	HRV window	string	required	available for every exported HRV window	Unique identifier of the exported HRV window.			dashboard-to-export traceability
export_timestamp_iso	HRV window	string	required	available for every exported HRV window	ISO 8601 timestamp at which the long-format export was serialized.			export provenance
pipeline_version	HRV window	string_or_null	required_nullable	populated when the calling application supplies its pipeline version	Version identifier of the processing pipeline that generated the row.			reproducibility metadata
export_schema_version	HRV window	string	required	available for every exported HRV window	Version identifier of the long-format export schema.			reproducibility metadata
window_start_timestamp_iso	HRV window	string	required	available for every exported HRV window	ISO 8601 timestamp marking the start of the HRV window.			temporal alignment
window_end_timestamp_iso	HRV window	string	required	available for every exported HRV window	ISO 8601 timestamp marking the end of the HRV window.			temporal alignment
elapsed_session_time_start_s	HRV window	float	required	available for every exported HRV window	Elapsed session time at the start of the HRV window.		s	temporal alignment
elapsed_session_time_end_s	HRV window	float	required	available for every exported HRV window	Elapsed session time at the end of the HRV window.		s	temporal alignment
phase_label	HRV window	categorical_string	required	available after event annotation; uses none when no phase is active	Phase label assigned by the event annotation layer, such as baseline, intervention, or recovery.			phase-aware segmentation
active_event_id	HRV window	string_or_null	required_nullable	populated while a user-defined event or phase is active	Identifier of the active event associated with the HRV window.			event synchronization
time_since_phase_start_s	HRV window	float_or_null	required_nullable	populated when the window is assigned to an active phase	Elapsed time from phase onset to the end of the HRV window.		s	event synchronization
rmsdd	HRV window	float_or_null	required_nullable	available after sufficient cleaned rolling-window data	Root mean square of eligible successive NN-interval differences calculated for the cleaned HRV window.		ms	downstream model input
sdnn_ms	HRV window	float_or_null	required_nullable	available after sufficient cleaned rolling-window data	Sample standard deviation of accepted NN intervals in the rolling HRV window.		ms	downstream model input
pnn50_percent	HRV window	float_or_null	required_nullable	available after sufficient eligible successive NN differences	Percentage of eligible successive NN-interval differences greater than 50 ms.		%	downstream model input
mean_hr_bpm	HRV window	float_or_null	required_nullable	available after sufficient accepted RR intervals	Rolling heart-rate estimate derived from accepted NN intervals.		beats/min	rolling feature construction
signal_reliability_score	HRV window	float	required	available for every exported HRV window	Signal-quality estimate derived from artifact burden, beat density, and data freshness.		0–1	signal-quality filtering
artifact_rate_percent	HRV window	float	required	available for every exported HRV window	Percentage of recent RR inputs rejected by the online artifact detector.		%	signal-quality filtering
psd_readiness_score	HRV window	float_or_null	required_nullable	available for every window; may be null or zero before spectral criteria are met	Quality gate combining frequency-analysis window fill and stationarity.		0–1	spectral-readiness gating
baseline_segment_id	HRV window	string_or_null	required_nullable	populated after completion of a valid baseline segment	Identifier linking the window to the baseline segment used for comparison.			baseline-relative modeling
baseline_available	HRV window	boolean	required	available for every exported HRV window	Indicates whether a valid baseline summary was available for this window.			baseline-relative modeling
baseline_reference_type	HRV window	string_or_null	required_nullable	populated after completion of a valid baseline segment	Baseline mean and sample standard deviation used for CSV-level standardized deviation fields.			baseline-relative modeling
baseline_window_count	HRV window	integer_or_null	required_nullable	populated after completion of a valid baseline segment	Number of HRV windows contributing to the baseline reference.		count	baseline-relative modeling
rmsdd_delta_from_baseline_ms	HRV window	float_or_null	required_nullable	populated after baseline initialization when RMSDD is available	Absolute RMSDD deviation from the baseline mean.		ms	baseline-relative modeling
rmsdd_percent_change_from_baseline	HRV window	float_or_null	required_nullable	populated after baseline initialization when the baseline mean is non-zero	RMSDD change relative to the baseline mean.		%	baseline-relative modeling
sdnn_delta_from_baseline_ms	HRV window	float_or_null	required_nullable	populated after baseline initialization when SDNN is available	Absolute SDNN deviation from the baseline mean.		ms	baseline-relative modeling
sdnn_percent_change_from_baseline	HRV window	float_or_null	required_nullable	populated after baseline initialization when the baseline mean is non-zero	SDNN change relative to the baseline mean.		%	baseline-relative modeling
pnn50_delta_from_baseline_percent	HRV window	float_or_null	required_nullable	populated after baseline initialization when pNNSD is available	Absolute pNNSD deviation from the baseline mean in percentage points.		percentage points	baseline-relative modeling
pnn50_percent_change_from_baseline	HRV window	float_or_null	required_nullable	populated after baseline initialization when the baseline mean is non-zero	Relative pNNSD change from the baseline mean; interpreted cautiously when baseline pNNSD is small.		%	baseline-relative modeling
mean_hr_delta_from_baseline_bpm	HRV window	float_or_null	required_nullable	populated after baseline initialization when heart rate is available	Absolute heart-rate deviation from the baseline mean.		beats/min	baseline-relative modeling
mean_hr_percent_change_from_baseline	HRV window	float_or_null	required_nullable	populated after baseline initialization when the baseline mean is non-zero	Heart-rate change relative to the baseline mean.		%	baseline-relative modeling
rmsdd_baseline_z	HRV window	float_or_null	required_nullable	populated after baseline initialization when baseline SD is non-zero	Baseline-standardized deviation calculated from the baseline mean and sample standard deviation.		z score	baseline-relative modeling
sdnn_baseline_z	HRV window	float_or_null	required_nullable	populated after baseline initialization when baseline SD is non-zero	Baseline-standardized deviation calculated from the baseline mean and sample standard deviation.		z score	baseline-relative modeling
pnn50_baseline_z	HRV window	float_or_null	required_nullable	populated after baseline initialization when baseline SD is non-zero	Baseline-standardized deviation calculated from the baseline mean and sample standard deviation.		z score	baseline-relative modeling
mean_hr_baseline_z	HRV window	float_or_null	required_nullable	populated after baseline initialization when baseline SD is non-zero	Baseline-standardized deviation calculated from the baseline mean and sample standard deviation.		z score	baseline-relative modeling
outside_baseline_corridor_boolean	HRV window	boolean_or_null	required_nullable	populated when a baseline corridor is available	Indicates whether at least one retained HRV metric lies outside its baseline corridor.			baseline-relative modeling
outside_baseline_corridor_metrics	HRV window	string_or_null	required_nullable	populated when a baseline corridor comparison is available	Semicolon-delimited metric names outside their baseline corridors; empty when none are outside.			baseline-relative modeling
interpretability_label	HRV window	categorical_string	required_nullable	populated when a completed segment summary overlaps the window	Engineering interpretability label assigned from segment-level signal quality.			signal-quality filtering

Note: Requiredness and availability refer to the long-format CSV export schema. Baseline-relative fields are populated only after a valid baseline summary is available. Variables representing composite physiological readouts are experimental engineering descriptors and are not validated clinical diagnostic, prognostic, stress, recovery, monitoring, or decision-support scores.

Supplementary Table S3. Real-world emergency simulation feasibility and signal-quality summary

session_id	stream_id	acquisition_source	sensor_stream	phase	phase_duration	n_exported_rr_updates	temporal_coverage_percent	complete_time_domain_percent	mean_signal_confidence	median_signal_confidence	active_signal_status_percent	mean_artifact_ratio_percent	p95_artifact_ratio_percent	phase_label_alignment_percent
501	501_A	Polar H10 BLE	Sensor 1	baseline	377.9	547	100.0	100.0	0.995	1.000	100.0	0.3	2.4	100.0
501	501_A	Polar H10 BLE	Sensor 1	intervention/simulation	1787.4	354.4	100.0	100.0	0.996	1.000	100.0	0.2	2.4	100.0
501	501_A	Polar H10 BLE	Sensor 1	recovery	338.4	399	99.8	100.0	0.997	1.000	100.0	0.2	1.4	100.0
501	501_B	Polar H10 BLE	Sensor 2	baseline	377.9	774	99.5	100.0	0.997	1.000	100.0	0.0	0.0	100.0
501	501_B	Polar H10 BLE	Sensor 2	intervention/simulation	1787.4	342.0	100.0	100.0	0.990	0.995	100.0	1.1	4.5	100.0
501	501_B	Polar H10 BLE	Sensor 2	recovery	338.4	581	99.8	100.0	0.988	0.996	100.0	1.4	4.9	100.0
502	502_A	Polar H10 BLE	Sensor 1	baseline	558.7	740	97.6	100.0	0.992	0.991	99.3	11.6	31.0	100.0
502	502_A	Polar H10 BLE	Sensor 1	intervention/simulation	814.7	1236	99.8	100.0	0.979	0.993	100.0	2.5	9.5	100.0
502	502_A	Polar H10 BLE	Sensor 1	recovery	361.2	461	99.4	100.0	0.996	1.000	100.0	0.4	2.7	100.0
502	502_B	Polar H10 BLE	Sensor 2	baseline	558.7	687	99.9	100.0	0.795	0.997	94.8	23.1	88.9	100.0
502	502_B	Polar H10 BLE	Sensor 2	intervention/simulation	814.7	1218	99.8	100.0	0.986	0.998	99.8	1.3	8.1	100.0
502	502_B	Polar H10 BLE	Sensor 2	recovery	361.2	395	99.6	100.0	0.791	0.971	96.8	23.8	91.7	100.0
503	503_A	Polar H10 BLE	Sensor 1	baseline	359.9	423	99.6	100.0	0.994	0.994	100.0	0.7	1.5	100.0
503	503_A	Polar H10 BLE	Sensor 1	intervention/simulation	743.0	994	99.9	100.0	0.976	0.994	96.4	2.9	12.6	100.0
503	503_A	Polar H10 BLE	Sensor 1	recovery	358.7	413	99.4	100.0	0.993	0.993	100.0	0.9	2.7	100.0
503	503_B	Polar H10 BLE	Sensor 2	baseline	359.9	516	99.4	100.0	0.919	0.923	98.8	9.4	26.3	100.0
503	503_B	Polar H10 BLE	Sensor 2	intervention/simulation	743.0	1374	100.0	100.0	0.974	0.980	100.0	2.7	8.0	99.9
503	503_B	Polar H10 BLE	Sensor 2	recovery	358.7	399	99.8	100.0	0.902	0.888	98.2	11.5	26.1	100.0
504	504_A	Polar H10 BLE	Sensor 1	baseline	354.0	328	99.8	100.0	0.968	0.980	100.0	0.3	12.1	100.0
504	504_A	Polar H10 BLE	Sensor 1	intervention/simulation	646.6	946	99.8	95.2	0.938	0.997	96.5	7.8	64.2	100.0
504	504_A	Polar H10 BLE	Sensor 1	recovery	389.1	371	99.5	97.8	0.940	0.924	99.7	7.7	17.6	100.0
504	504_B	Polar H10 BLE	Sensor 2	baseline	354.0	383	99.9	99.4	0.772	0.928	65.5	25.1	89.8	100.0
504	504_B	Polar H10 BLE	Sensor 2	intervention/simulation	646.6	895	99.7	99.4	0.873	0.887	89.1	15.1	35.0	100.0
504	504_B	Polar H10 BLE	Sensor 2	recovery	389.1	450	99.4	90.9	0.861	0.920	81.1	15.7	58.7	100.0
505	505_A	Polar H10 BLE	Sensor 1	baseline	358.3	152	99.9	100.0	0.998	1.000	100.0	0.0	0.0	100.0
505	505_A	Polar H10 BLE	Sensor 1	intervention/simulation	620.0	992	99.9	100.0	0.999	0.999	100.0	0.7	2.1	100.0
505	505_A	Polar H10 BLE	Sensor 1	recovery	319.3	508	99.5	100.0	0.998	1.000	100.0	0.2	1.0	100.0
505	505_B	Polar H10 BLE	Sensor 2	baseline	358.3	476	99.6	100.0	0.976	0.988	100.0	3.0	14.0	100.0
505	505_B	Polar H10 BLE	Sensor 2	intervention/simulation	620.0	947	99.8	98.8	0.963	0.990	98.6	4.0	22.6	100.0
505	505_B	Polar H10 BLE	Sensor 2	recovery	319.3	435	100.0	67.8	0.734	0.938	58.9	31.1	91.4	100.0

Note: Rows summarize phase-level technical feasibility and signal-quality metrics from five dyadic emergency simulation sessions with two Polar H10 BLE streams per session. Percentages refer to the corresponding annotated phase. The table documents operational real-world acquisition, stream-level separation, phase alignment, signal-quality preservation, and export feasibility; it does not represent validated stress, recovery, diagnostic, prognostic, monitoring, or decision-support performance.

Supplementary Table S4. External expert-annotation validation of the firmware-equivalent ECG-to-RR detection route

Method	Reference beats	True positives	False positives	False negatives	Sensitivity	Positive predictive value (PPV)	F1 score	Median absolute timing error (ms)	Record-level median F1 score	Record-level interquartile range (IQR)
Firmware-equivalent Pan-Tompkins-based detector	109,494	107,641	1,405	1,853	0.983	0.987	0.985	86,000	0.998	0.005
Hamilton benchmark	109,494	107,485	1,395	2,009	0.982	0.987	0.984	61,556	0.998	0.006

Note. Electrocardiogram (ECG); R-R interval (RR interval); positive predictive value (PPV); interquartile range (IQR).

Performance was evaluated against 109,494 expert beat annotations from all 48 MIT-BIH Arrhythmia Database records using fixed one-to-one ± 150 -ms matching. Timing error is the absolute error among matched beats.

Supplementary Table S5. Record-level ECG-to-RR detection performance across the MIT-BIH Arrhythmia Database

MIT-BIH record	Firmware-equivalent F1 score	Hamilton F1 score	Difference in F1 score	Firmware sensitivity	Firmware positive predictive value	Hamilton sensitivity	Hamilton positive predictive value
100	1,000	1,000	-0,0002	0,999	1,000	1,000	1,000
101	0,998	0,999	-0,0005	0,999	0,997	0,999	0,998
102	1,000	1,000	-0,0002	1,000	1,000	1,000	1,000
103	0,999	0,999	-0,0000	0,998	1,000	0,998	1,000
104	0,996	0,991	+0,0047	0,999	0,992	0,993	0,988
105	0,992	0,990	+0,0023	0,997	0,987	0,994	0,985
106	0,998	0,987	+0,0107	0,997	0,999	0,978	0,996
107	0,993	0,997	-0,0044	0,992	0,994	0,994	1,000
108	0,700	0,635	+0,0648	0,769	0,642	0,693	0,586
109	0,999	0,999	-0,0004	0,998	1,000	0,998	1,000
111	1,000	0,999	+0,0005	1,000	1,000	1,000	0,999
112	1,000	1,000	-0,0002	1,000	1,000	1,000	1,000
113	0,999	0,999	+0,0006	0,999	1,000	0,999	0,999
114	0,999	0,999	-0,0003	0,999	0,999	0,999	0,999
115	1,000	0,976	+0,0240	0,999	1,000	0,990	0,962
116	0,994	0,993	+0,0006	0,989	0,999	0,989	0,998
117	1,000	0,963	+0,0368	1,000	1,000	0,971	0,955
118	1,000	1,000	-0,0002	1,000	1,000	1,000	1,000
119	0,999	1,000	-0,0003	0,999	0,999	1,000	0,999
121	0,999	0,998	+0,0016	0,999	1,000	0,998	0,997
122	1,000	1,000	-0,0002	1,000	1,000	1,000	1,000
123	0,999	0,995	+0,0040	0,997	1,000	0,995	0,995
124	0,996	0,996	+0,0000	0,996	0,996	0,993	0,999
200	0,998	0,998	-0,0006	0,998	0,998	0,997	1,000
201	0,977	0,982	-0,0046	0,963	0,992	0,964	1,000
202	0,994	0,996	-0,0019	0,992	0,996	0,993	0,999
203	0,978	0,986	-0,0083	0,969	0,986	0,975	0,997
205	0,998	0,998	+0,0009	0,997	1,000	0,995	1,000
207	0,935	0,945	-0,0102	0,991	0,885	0,984	0,909
208	0,929	0,837	+0,0923	0,924	0,935	0,720	0,999
209	1,000	1,000	+0,0005	1,000	1,000	1,000	0,999
210	0,991	0,982	+0,0088	0,986	0,995	0,965	0,999
212	1,000	0,999	+0,0005	1,000	1,000	1,000	0,999
213	0,997	0,998	-0,0008	0,996	0,998	0,995	1,000
214	0,999	0,998	+0,0009	0,998	1,000	0,997	0,999
215	1,000	1,000	+0,0001	0,999	1,000	0,999	1,000
217	0,998	0,998	+0,0002	0,996	0,999	0,996	0,999
219	0,998	0,995	+0,0033	0,997	1,000	0,991	1,000
220	1,000	0,999	+0,0007	1,000	1,000	0,999	0,999
221	0,997	0,996	+0,0015	0,996	0,999	0,992	1,000
222	0,998	0,998	+0,0004	0,999	0,998	0,999	0,997
223	0,998	0,997	+0,0010	0,998	0,998	0,995	1,000
228	0,786	0,996	-0,2098	0,654	0,985	0,997	0,995
230	1,000	0,999	+0,0007	1,000	1,000	0,999	0,999
231	1,000	0,985	+0,0151	0,999	1,000	0,997	0,973
232	0,970	0,999	-0,0283	0,947	0,995	1,000	0,997
233	0,998	0,997	+0,0008	0,997	0,999	0,994	1,000
234	1,000	0,999	+0,0002	0,999	1,000	0,999	1,000

Note. Electrocardiogram (ECG); R-R interval (RR interval); positive predictive value (PPV). Difference in F1 score is firmware-equivalent detector minus Hamilton benchmark.

Records 108, 207, 208, and 228 had firmware-equivalent F1 scores below 0.95 and are shown in bold.

Supplementary Table S6. RR-stream integrity and Signal Confidence across controlled noise levels

Signal-to-noise ratio (SNR)	Number of 10-s windows	RR-intact windows, n (%)	Median Signal Confidence	IQR of Signal Confidence	Signal Status Active (%)	Signal Status Active or Noisy (%)	Orphanidou usable (%)	R-peak sensitivity	R-peak positive predictive value (PPV)	Pooled R-peak F1 score
Clean	360	358 (99.4)	0,877	0,379	60.0	80.8	39.7	1,000	1,000	1,000
24 dB	156	156 (100.0)	0,899	0,337	64.7	84.6	33.3	1,000	1,000	1,000
18 dB	156	148 (94.9)	0,905	0,391	60.9	77.6	14.7	0,996	0,996	0,996
12 dB	156	122 (78.2)	0,802	0,434	56.4	74.4	1.9	0,995	0,965	0,979
6 dB	156	23 (14.7)	0,512	0,213	17.3	53.2	0.0	0,969	0,705	0,816
0 dB	156	1 (0.6)	0,494	0,193	7.7	48.1	0.6	0,851	0,547	0,666
-6 dB	156	0 (0.0)	0,475	0,181	1.9	36.5	0.0	0,610	0,420	0,497

Note. R-R interval (RR interval); signal-to-noise ratio (SNR); interquartile range (IQR); positive predictive value (PPV).
The primary population comprised clean source windows and actual noise-exposed intervals only (n = 1,296 non-overlapping 10-s windows). RR-intact indicates zero false-positive and zero false-negative beat detections within a window relative to expert annotations.

Supplementary Table S7. Performance of RR-stream quality indicators for expert-defined RR degradation

A. Binary decision rules								
Quality indicator	Decision rule	Sensitivity for degraded RR windows	Specificity for intact RR windows	Positive predictive value	Negative predictive value	Balanced accuracy	F1 score	Matthews correlation coefficient (MCC)
Signal Status	Non-Active indicates degraded	0,865	0,589	0,560	0,878	0,727	0,680	0,446
Signal Status	Low Confidence or Signal Lost indicates degraded	0,500	0,781	0,580	0,721	0,640	0,537	0,291
Orphanidou signal-quality index	Unacceptable indicates degraded	0,994	0,271	0,452	0,986	0,632	0,621	0,341
B. Continuous discrimination								
Quality indicator	Area under the receiver operating characteristic curve (AUROC)	Area under the precision-recall curve (AUPRC)						
Signal Confidence	0,754	0,545						
Orphanidou signal-quality index	0,662	0,336						

Note. R-R interval (RR interval); positive predictive value (PPV); negative predictive value (NPV); Matthews correlation coefficient (MCC); area under the receiver operating characteristic curve (AUROC); area under the precision-recall curve (AUPRC).

Degraded windows contained at least one false-positive or false-negative beat detection relative to expert annotations. The primary population comprised clean source windows and actual noise-exposed intervals only.

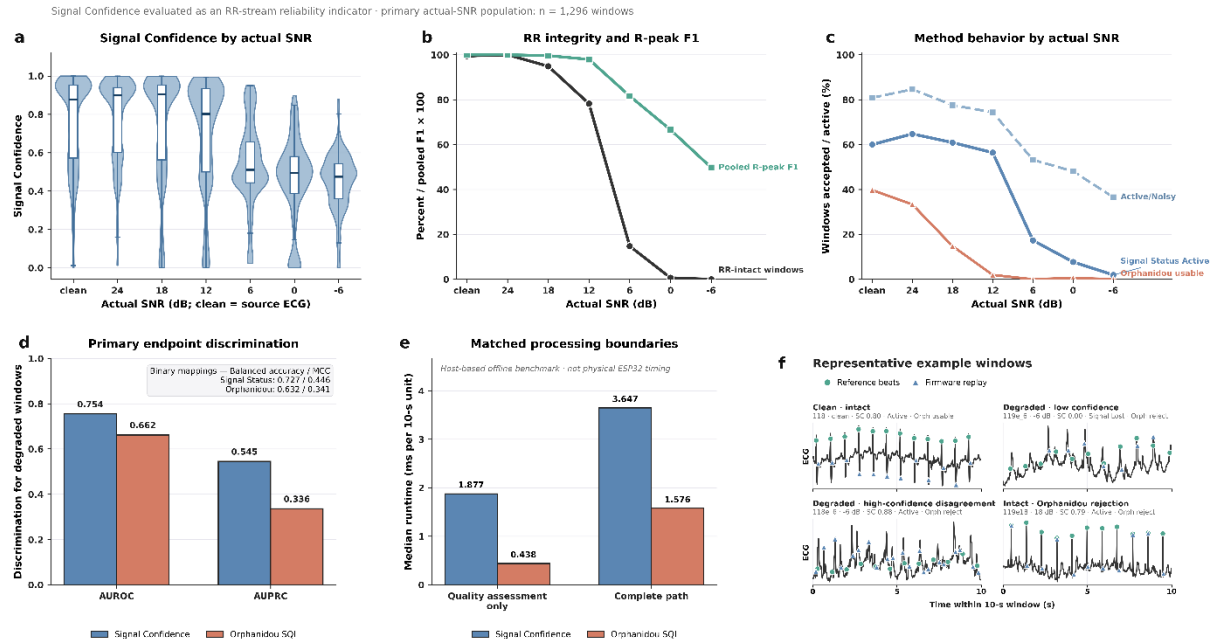
Signal Confidence represents downstream RR-stream reliability, whereas the Orphanidou comparator evaluates electrocardiogram signal quality using morphology- and rhythm-based criteria.

Supplementary Table S8. Computational runtime of Signal Confidence and Orphanidou quality assessment

Method	Processing boundary	Median runtime per 10-s unit (ms)	Interquartile range (IQR) per 10-s unit (ms)	Real-time factor
Signal Confidence	Quality assessment only	1,877	0,005	0,000188
Signal Confidence	Complete ECG-to-RR-to-Signal Confidence path	3,647	0,009	0,000365
Orphanidou signal-quality index	Quality assessment only	0,438	0,002	0,000044
Orphanidou signal-quality index	Complete ECG-to-Hamilton-to-Orphanidou path	1,576	0,004	0,000158

Note. Electrocardiogram (ECG); R-R interval (RR interval); interquartile range (IQR).

Runtime values represent controlled host-based offline execution and do not represent physical ESP32 execution time. All boundaries used the same 2,520 non-overlapping 10-s analysis units. IQR values were converted from the source batch-runtime IQR to milliseconds per 10-s unit without changing the underlying measurements.



Supplementary Figure S1. Controlled-noise validation of RR-stream quality under electrocardiogram degradation. Signal Confidence was evaluated using the MIT-BIH Noise Stress Test Database across clean recordings and noise-exposed intervals at SNRs of 24, 18, 12, 6, 0, and -6 dB. (a) Signal Confidence across SNR conditions. (b) Proportion of RR-intact windows and pooled R-peak F1 score. (c) Signal Status and Orphanidou-based usability classifications across SNR conditions. (d) Discrimination of expert-defined RR-sequence degradation using AUROC, AUPRC, balanced accuracy, and Matthews correlation coefficient. (e) Host-based runtime under matched processing boundaries. (f) Representative clean, degraded, and method-disagreement windows with expert and algorithmic beat detections. Signal Confidence represents downstream RR-stream reliability and is conceptually distinct from morphology-based ECG signal-quality assessment.