TrackPaw

Respiratory Rate Estimation in Single-Housed Mice

Validation against a radar reference

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Summary

- **What TrackPaw measures.** TrackPaw estimates respiratory rate during inactivity from the sensorised floor of the home cage, without restraint or a respiratory sensor attached to the animal. When a mouse is inactive, breathing produces a small periodic force on the cage floor. TrackPaw recovers that rate and reports one value per animal per minute.
- **How it was validated.** TrackPaw output was compared minute by minute with a simultaneous radar respiration reference. The two systems recorded simultaneously for 413 hours across 10 animals and 4 devices. Both methods reported a rate in 1712 minutes, which form the scored set. Agreement with the radar was strong: a near-zero **bias of −1.2 BPM** with **95 % limits of agreement of −7.7–5.2 BPM** across the observed-rate range (reference mean 197 BPM). In plain terms, 99 % of compared minutes agree within 6 % of the radar (Pearson r = 0.99).
- **How to read the output.** The metric is opportunistic by design. It reports when the animal is still enough for a clean breathing signal and stays silent during movement rather than filling gaps with guesses. A missing minute is no measurement, not a respiratory rate of zero.
- **Scope.** All claims in this paper are for single-housed mice. Group-housed operation is active work and remains outside the scope of this paper.

Introduction

Respiratory rate is a sensitive physiological readout in preclinical research across respiratory and cardiovascular safety pharmacology, disease models, and general health and welfare assessment. The hard part is not deciding whether breathing matters. It is measuring it without changing the breathing being measured.

Established methods usually force a trade-off. Whole-body or head-out plethysmography can provide controlled measurements (Hoymann, 2007), but the animal is removed from its home cage and placed into a short experimental session. Telemetry can extend observation, but it requires surgery and an attached or implanted device; recovery and welfare can be shaped by the housing context itself (Van Loo et al., 2007). In both cases, the method can introduce handling, restraint, novel-environment, or recovery effects that are physiologically meaningful in their own right.

TrackPaw takes a different route: the home cage becomes the instrument. It uses the sensorised cage floor to recover respiratory rate during inactivity while the animal remains in its normal cage, with bedding and enrichment, without restraint or a respiratory sensor attached to it. This follows the broader move toward automated, longitudinal home-cage monitoring (Bains et al., 2018; Kahnau et al., 2023). This paper defines the resulting metric, describes the measurement principle, and validates the single-housed implementation against a simultaneous radar reference.

Capturing the breathing signal

Before the metric can be validated, the system has to capture the breathing signal itself. This section describes how it does that: the floor sensors, the physical principle that makes breathing observable, and the signal processing that turns force into a respiratory rate.

Hardware and sensors

The TrackPaw system combines two sensor systems built into the cage floor: **force-sensing cells** and **RFID readers**. The force sensing cells continuously measure the load each animal places on the floor, and the RFID readers continuously identify which animal is where. Together they turn the home cage itself into the instrument — capturing data in the animals' home environment, with normal bedding and enrichment, and without restraint or a respiratory sensor attached to the animal.

The animal-facing floor is a grid of independent sensing cells. The results in this paper were collected on the EP4[1] platform in the high-variant type 3 cage form factor,[2] with a 5 × 3 cell matrix. Each cell is an independent plate supported by three piezoelectric force sensors and carries its own RFID reader. The force signals are sampled at **~120 Hz**. Each animal carries an FDX-B RFID transponder, and each cell's RFID reader scans at **~1 Hz**, identifying which tagged animal is over it.

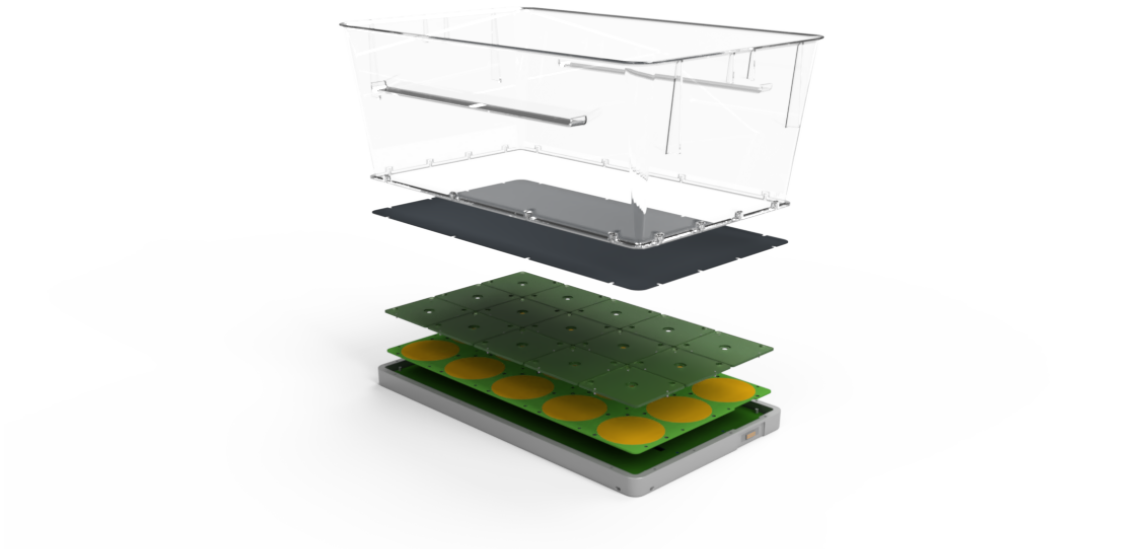


Figure 1: Exploded view of the sensorised cage floor: the device, its grid of cells, and the per-cell RFID antennas, tiled into the 5 × 3 matrix.

Measurement principle

A still mouse loads the cell or cells beneath it with its body weight. Breathing modulates that load: the thoracic movement of each breath produces a small, periodic change in the vertical force the animal exerts on the floor. Because the force grid is sampled fast enough to resolve breathing, this periodic force modulation is directly observable in the cell or cells beneath a still animal. When the animal moves, the same modulation is swamped by larger forces. That is the physical reason the metric is opportunistic.

Because breathing is sensed as a change in mechanical load rather than as a visual cue, the signal does not depend on an unobstructed view of the animal: the force passes through the nest, bedding, and enrichment the animal rests on, and is read in complete darkness.

[1] Engineering prototype 4.

[2] The cage measures 365 mm × 204 mm at the floor (a 745 cm^2 floor area), 425 mm × 265 mm at the top, and 150 mm high.

Signal processing

The rate is computed in two stages: per-cell breath detection, then aggregation into a per-minute rate.

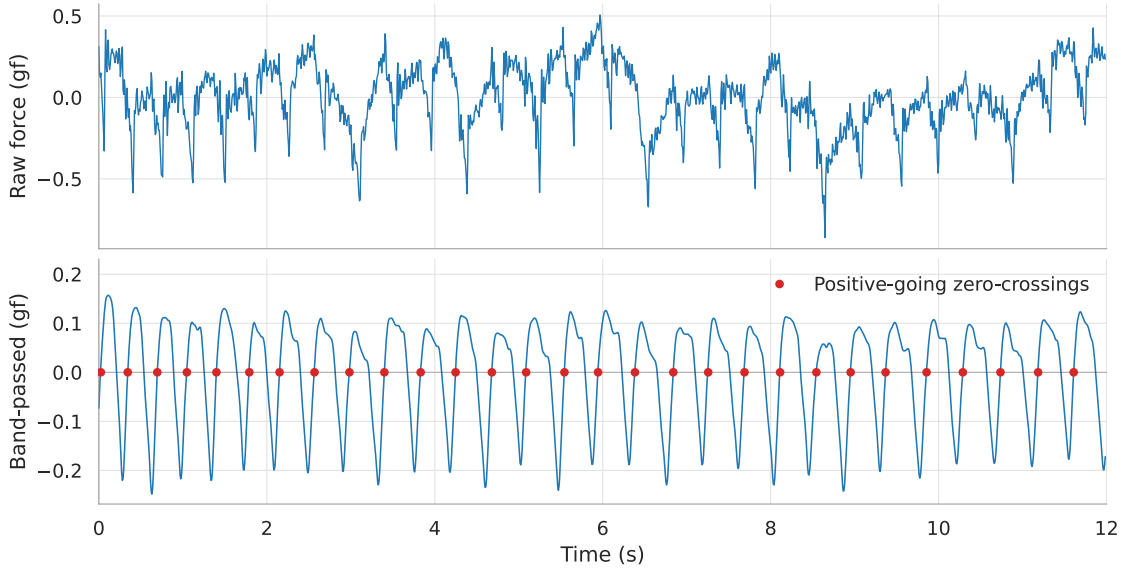


Figure 2: Breath detection on a single cell over a 12 s window: the raw force signal (top, mean removed) and its 1–10 Hz band-passed form (bottom) with the positive-going zero-crossings from which the rate is counted.

Per-cell detection. Each cell's force stream is band-pass filtered to the breathing band (1–10 Hz). Positive-going zero-crossings are counted over a rolling buffer of 50 crossings. The cell's instantaneous rate is the inverse of the mean inter-crossing period, expressed in BPM. A cell reports a rate only while its crossings are **regular** (a periodicity gate on the normalised period spread), so irregular, movement-driven signals are rejected. This regularity requirement is what concentrates output in the calm minutes.

Aggregation. Over the one-minute window, the rates from the cells beneath the animal are pooled and collapsed by their **median**. A minute yields a value only when it carries enough breath detections to support a stable median — at least half the breaths expected at its own rate. We call this threshold the **50 % aggregation gate**. Minutes below it are left unreported.

The respiratory-rate metric

This section defines *what* the metric reports, independent of how the signal is captured or validated.

Quantity. The metric reports a single animal's **respiratory rate** — breaths per minute (BPM) — during inactive minutes, when movement is low enough for breathing to be resolved from the floor signal. It is a rate trend, not a breath waveform and not an estimate of respiratory effort.

Reporting cadence. TrackPaw reports at most one value per animal per minute. Each value summarises one minute of breathing during inactivity, and is reported only when the signal is clear and sustained enough to support a reliable rate.

Stillness. TrackPaw reports only while the animal is still enough for breathing to appear as a clean, regular periodic signal. Locomotion, grooming, sniffing, and arousal can mask that signal. During those periods no rate is reported. The metric is therefore **sparse by design**: it produces readings on inactive minutes and leaves active minutes blank. A missing value is the absence of a measurement, not a respiratory rate of zero.

Validation against an independent reference

Reference: simultaneous radar

An Acconeer A121 pulsed coherent radar (60 GHz) served as the reference. It was mounted at the centre of the cage lid, looking down into the cage, and recorded simultaneously with TrackPaw. TrackPaw reads force through the cage floor. The radar reads motion through reflected radio waves. The comparison therefore uses two independent physical signals, not two algorithms reading the same one. Radar respiration sensing has been validated as a contactless respiratory-monitoring modality in human clinical settings (van Loon et al., 2016), and contactless respiratory-rate measurement has also been demonstrated in rodents using video recordings (Kunczik et al., 2019).

The radar is used as an independent reference, not as an absolute ground truth. Both systems estimate live breathing opportunistically, so the validation measures **agreement** between methods rather than error against a perfect instrument.

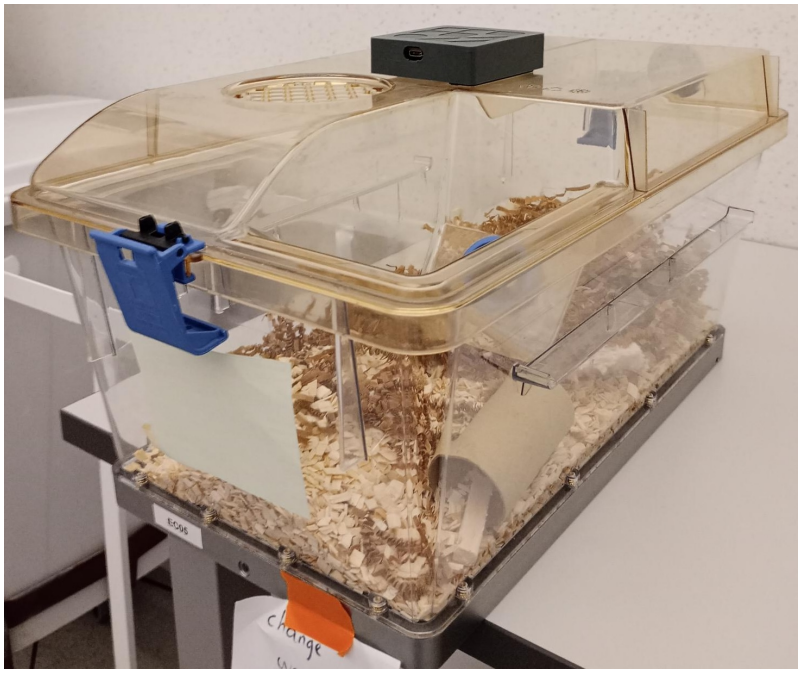


Figure 3: The radar reference in place: an Acconeer A121 mounted centrally on the cage lid, viewing the animal from above. The water bottle was removed only to take this photograph; food pellets were provided on the cage floor.

The radar pipeline starts from raw radar data rather than a packaged respiration monitor. The radar illuminates the cage and records the complex reflection of its own signal. Chest-wall motion modulates the phase of that reflection, and the rate is read as the dominant frequency in a short-time Fourier spectrum of the return. Against TrackPaw's zero-crossing count of a mechanical force signal, this is a different physical quantity and a different estimator. Small per-minute differences are therefore expected even when both methods are tracking the same underlying breathing. The radar also carries

its own motion gate and falls silent while the animal moves. Because it senses through a different channel, the two methods can be silent during different minutes.

For comparison, the radar and TrackPaw outputs are aligned by animal identity and one-minute time bucket.

Dataset

The validation dataset contains 413 hours (24 772 minutes) of simultaneous TrackPaw and radar recording across 10 animals and 4 devices. Across the full dataset, both methods reported a rate in 1712 minutes. These minutes form the scored set used in the comparison below.

The animals were C57BL/6 mice, a mix of males and females, aged 15–16 weeks, recorded in their home cage with **normal bedding and enrichment present**. Each animal carried an AEG-ID 162 FDX-B RFID transponder implanted subcutaneously at the neck.

Scoring

The agreement analysis uses only minutes where *both* estimators reported a rate for that animal. Missing minutes are not filled with zeros, since respiratory rate has no meaningful zero. Reporting overlap is analysed separately as coverage in the Results.

The scored set matches what TrackPaw reports in normal use: minutes must clear the aggregation gate defined above. Because the comparison is between two independent estimators rather than against an absolute truth, the primary statistic is the **spread of their per-minute differences**. We report agreement in Bland–Altman terms: bias (mean signed difference), difference spread, and 95% limits of agreement, with Pearson *r* alongside (Bland and Altman, 1986).

While the sample size is large, the minutes are not independent: they come from one mouse strain recorded under similar conditions. The limits of agreement describe this setup; they are not a precise interval for new hardware or cohorts.

Results

Agreement with the radar reference

When both systems report a rate for the same minute, TrackPaw's respiratory-rate estimate agrees closely with the simultaneous radar reference. The per-minute differences cluster near zero: a bias of −1.2 BPM with 95 % limits of agreement from −7.7–5.2 BPM across the observed-rate range (reference mean 197 BPM). Put plainly, 99 % of compared minutes fall within 6 % of the radar rate. The validation dataset contains 413 hours (24 772 minutes) of simultaneous TrackPaw and radar recording. Across the full dataset, 1712 animal-minutes carried both a TrackPaw rate and a radar rate and entered this agreement comparison. The appendix groups these per-minute differences by rate, showing that agreement holds across the observed-rate range rather than only in aggregate. Pearson $r = 0.99$ is included as a descriptive summary of the paired minutes; the bias and limits of agreement are the primary agreement summary.

Statistic	Value
Reference mean rate	197 BPM
Bias (mean signed difference)	−1.2 BPM
Difference spread (SD)	3.3 BPM
95% limits of agreement	−7.7–5.2 BPM
Pearson correlation *r*	0.99
Scored animal-minutes	1712

Table 1: Agreement between TrackPaw and the radar reference, single-housed scored set.

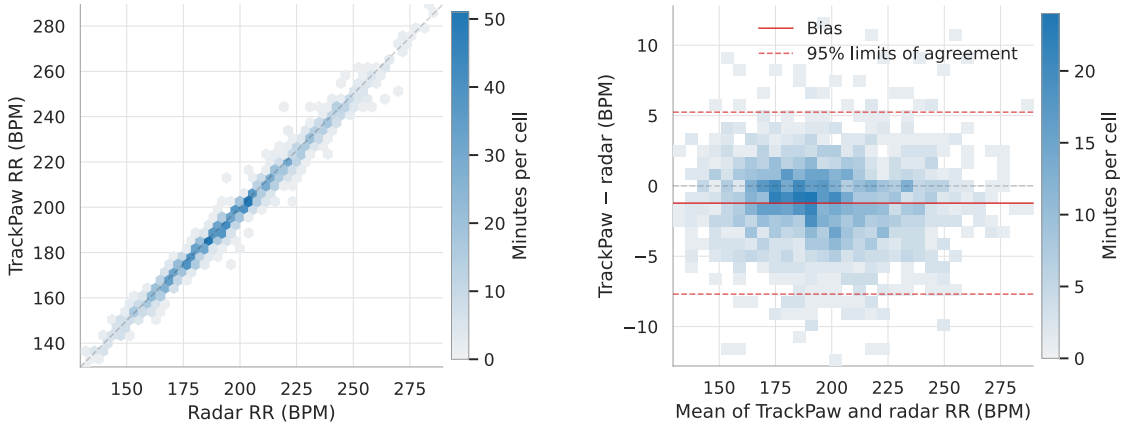


Figure 4: Agreement between TrackPaw and the radar reference on the scored set. Left: per-minute TrackPaw rate against the radar as a two-dimensional density plot, with the line of identity. Right: Bland–Altman — per-minute difference against the mean, with the bias line and the 95% limits of agreement.

The example below shows the paired rates over a two-hour window, with TrackPaw and the radar following the same changes over time.

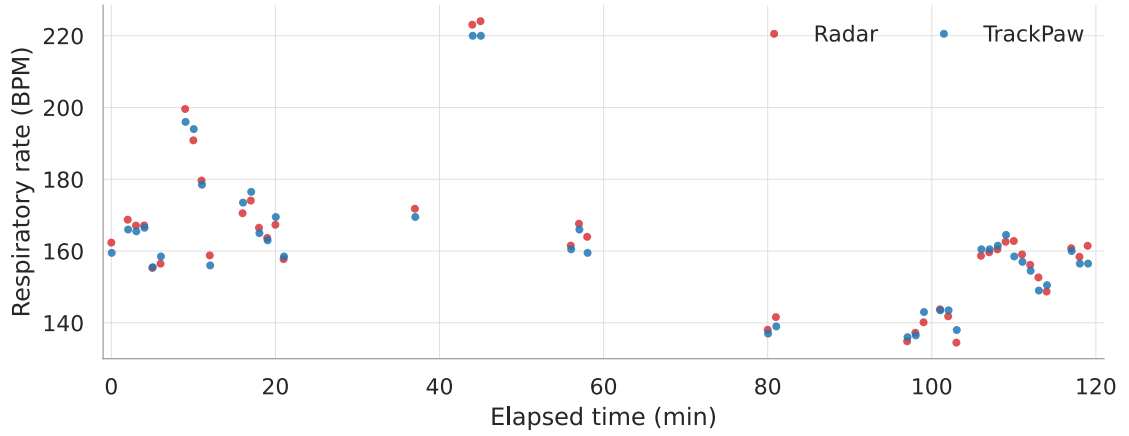


Figure 5: Agreement over time on an example session: per-minute respiratory rate from TrackPaw and the simultaneous radar reference across a two-hour window. Only minutes where both methods reported a rate are shown. Gaps mark minutes outside this paired agreement view, not TrackPaw silence alone.

Coverage

Coverage is separate from agreement because the metric is opportunistic. TrackPaw reported a rate on 72 % of the minutes where the radar reported a rate during the simultaneous recording period. Viewed the other way, the radar reported on 21 % of TrackPaw's reported minutes. These coverage figures describe how often each method speaks during the simultaneous recording period; they are separate from the agreement statistics above, which use only the 1712 minutes where both methods spoke. The asymmetry is expected: the two systems reject motion through different physical channels and are therefore silent on different minutes.

The appendix checks the link between reporting and stillness directly against TrackPaw's own movement signal.

Rate-recovery ceiling (synthetic context)

Synthetic sessions test rate recovery in isolation. In these runs the simulated breathing rate is known and varied across the physiological range. With no sensor noise, the difference spread is 0.017 BPM (r = 1.00). With realistic sensor noise, the spread is 0.484 BPM (r = 1.00), still well under 1 BPM.

The synthetic result does not replace live validation. It provides context for the live result: unlike the synthetic test, the live comparison includes two physical sensing channels, two estimators, animal movement, and within-minute variation in breathing.

Interpretation

Claim. TrackPaw can recover a respiratory-rate trend during inactivity from the home-cage floor in single-housed mice. When both TrackPaw and the radar reference report a rate for the same minute, the two methods agree closely: a bias of −1.2 BPM, with 95 % limits of agreement from −7.7–5.2 BPM.

Coverage. Coverage means how often the metric reports, not how accurate each reported value is. It is also not a confidence score. The metric reports during inactive minutes and leaves minutes affected by movement blank. For downstream analysis, aggregate reported minutes into longer respiratory-rate summaries and treat gaps as unobserved time.

Agreement. The radar is an independent estimator of live breathing, not an absolute standard. Any difference between radar and TrackPaw includes within-minute variation in breathing, different physical sensing channels, different rejection of movement, and estimator noise on both sides. The synthetic result is therefore useful context: when the true rate is known, TrackPaw's algorithm recovers it with a difference spread well under 1 BPM. The live result describes method-to-method agreement under real conditions.

Scope and limitations

Single-housed only. Every live-animal result in this paper is from single-housed animals, because the radar reference exists only for a single-housed cohort. The results should be read as a validation of single-housed operation, not group-housed operation.

One strain, narrow conditions. The validation cohort is a single mouse strain (C57BL/6) within a narrow age band, recorded under similar housing conditions. Body size, posture, and baseline rate shape the floor signal, so agreement is not yet established for other strains, ages, or substantially different conditions.

Opportunistic reporting. The metric reports during inactive minutes, when breathing can be resolved cleanly from the floor signal. During movement-heavy minutes it leaves a gap rather than inventing a rate. Analyses should treat those gaps as unobserved time and aggregate the reported minutes into the time scale relevant to the study.

Rate, not effort. The metric reports rate. It does not report tidal volume, breathing effort, or waveform morphology.

Conclusion and future work

TrackPaw estimates respiratory rate during inactivity in single-housed mice. It does so from the sensorised cage floor, without restraint or a respiratory sensor attached to the animal. The validation dataset contains 413 hours of simultaneous TrackPaw and radar recording across 10 animals and 4 devices. Both methods reported a rate in 1712 minutes. Across those minutes, the bias was −1.2 BPM, with 95 % limits of agreement of −7.7–5.2 BPM (Pearson r = 0.99). Synthetic rate-recovery tests show that, when the true breathing rate is known, the estimator recovers it with a difference spread well under 1 BPM.

The metric is deliberately sparse. It reports during inactive minutes and stays silent during movement, preserving the distinction between a reliable observation and no observation.

Future work has three priorities:

- Repeat the trials across additional mouse strains to confirm the result generalises beyond the C57BL/6 cohort reported here.
- Validate group-housed operation.
- Show directly that the metric detects pharmacological or disease-induced changes in respiratory rate, bridging measurement agreement to study-endpoint use.

For group housing, the main challenge is **attribution**: assigning each breathing signal to the correct co-housed animal. The current radar system also cannot attribute breathing to individual co-housed animals, so it cannot provide a per-animal reference. Group-housed validation therefore requires both reliable attribution and an independent reference capable of resolving individual animals.

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Appendix: agreement across the rate range

The Results section reports agreement across the scored set as a whole. This appendix checks whether that agreement is consistent across the observed rate range.

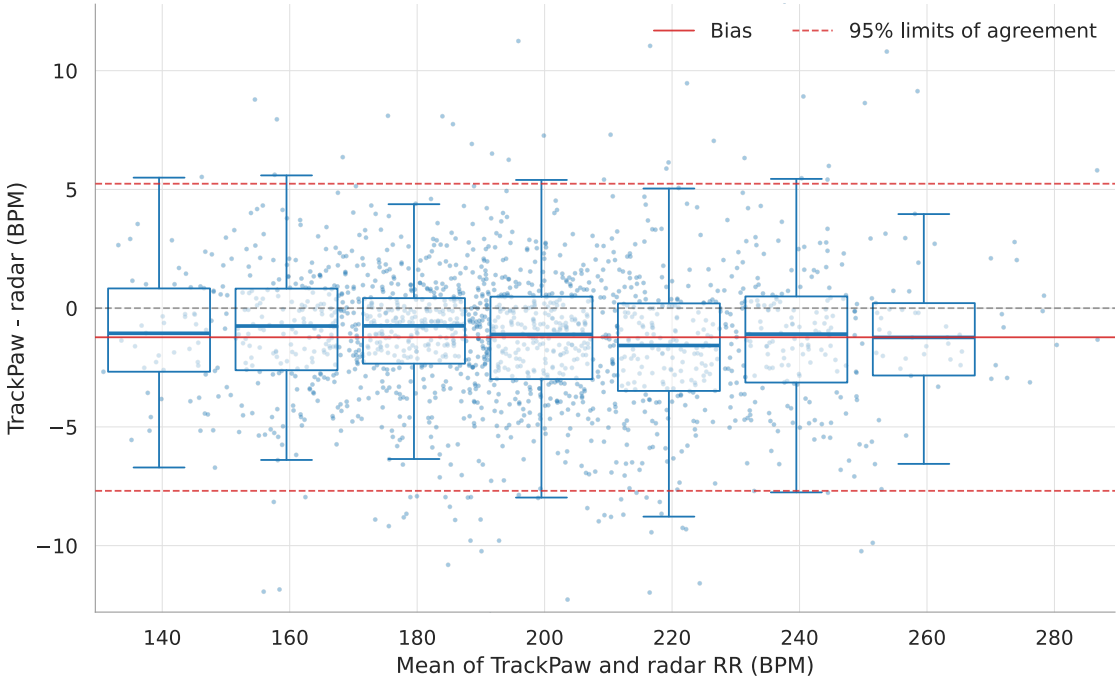


Figure 6: Per-minute agreement across the rate range. Points show the TrackPaw-minus-radar difference against the mean of the two rates. Boxplots summarise those differences within mean-rate bands with sufficient data. The bias and 95 % limits of agreement match the Results figure: −1.2 BPM and −7.7–5.2 BPM.

Across the observed range, the difference distributions stay centred close to zero with similar spread from band to band. This indicates that the headline agreement is not driven by one dense part of the rate distribution hiding poorer agreement elsewhere.

Appendix: reporting follows stillness

Respiratory-rate reporting should occur when the animal is still enough for the breathing signal to dominate the floor signal. This appendix checks that behaviour against TrackPaw's own per-minute travel distance. It is a self-consistency check, not validation against an external reference.

Across all animal-minutes in the dataset, reporting is concentrated almost entirely in still minutes: 99.9 % of minutes with a reported rate are classified as still by the travel signal, while only 0.1 % of minutes with movement carry one. Stillness is necessary, but not sufficient: many no-travel minutes still carry no rate.

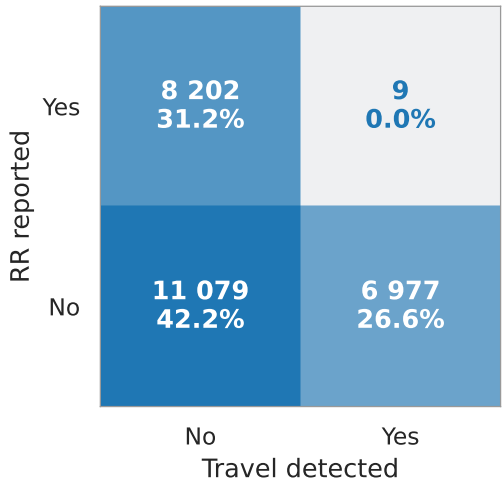


Figure 7: Presence of a reported rate against per-minute movement, across all animal-minutes in the dataset.

The same pattern is visible within a single recording. In this full-day example, reported rates cluster through calm stretches and fall away during bouts of movement.

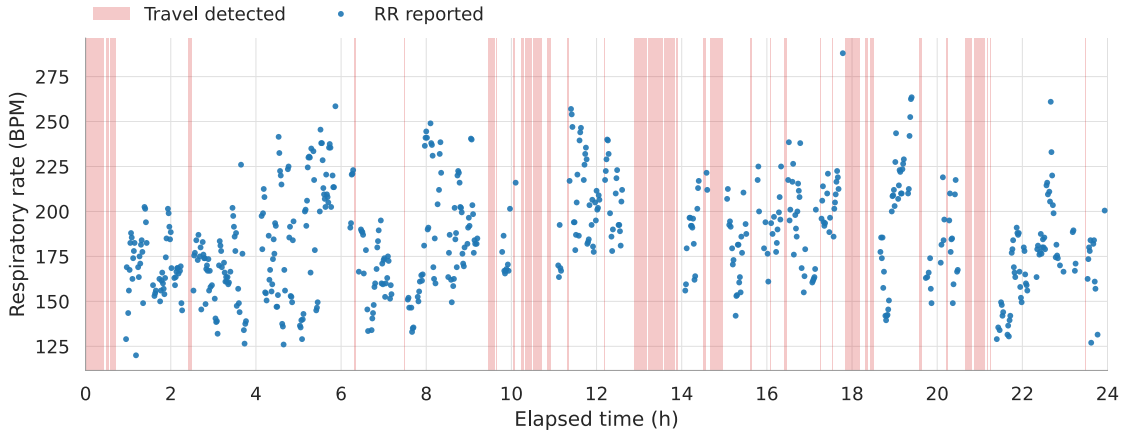


Figure 8: Example animal over 24 hours: reported respiratory-rate minutes (points) and minutes with movement (shaded).