

COLLECTOR TRANSIT AND SWEAT LACTATE TIMING DURING INTERMITTENT EXERCISE

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ABSTRACT

During intermittent exercise, an electronic sweat-lactate timestamp can fall in a different work or recovery interval from the entry of the sampled liquid. This article examines collector transit, reservoir carryover and the precision of sweat-derived physiological endpoints. This study examined nine human exercise investigations. Participant counts, sampling sites, exercise intervals, blood comparisons and prediction errors were evaluated alongside conservation-of-volume and solute-balance equations for plug transport and a mixed reservoir. In 40 men, sweat-minus-blood threshold timing had a mean difference of $+19.3$ s and individual agreement limits of -126.2 to $+164.7$ s. In 24 swimmers, four sweat thresholds could not be determined during interrupted testing. For a calculated $10\text{-}\mu\text{L}$ plug path supplied at 4 and $0.25\text{ }\mu\text{L min}^{-1}$ during alternating 2-min work and recovery intervals, liquid entering at the first work onset reaches the sensor at 4.375 min, during the second effort. A separate $10\text{-}\mu\text{L}$ mixed reservoir retains 7.81% of its starting contents after 12 min and reaches 95% replacement at 13.114 min. That replacement fraction limits residual error to 5% of a concentration step, rather than 5% of total measurement error. Individual-bout interpretation requires sensing-path flow, the upstream liquid volume and an inlet-time interval, followed by independent testing of the concentration, threshold or prediction endpoint.

Keywords: sweat lactate; wearable biosensor; intermittent exercise; microfluidic transport; sample residence time; lactate threshold.

INTRODUCTION

Tattoo electrodes measure lactate in perspiration, integrated arrays combine chemical measurements with skin-mounted electronics, and microfluidic patches capture and route sweat (Jia et al., 2013; Gao et al., 2016; Koh et al., 2016). Xuan et al. integrated a lactate electrode, fluid handling and a phone interface into a sports device (Xuan et al., 2023). These arrangements measure a local chemical concentration. Blood-lactate estimation, threshold detection and comparison of successive efforts each require a separate physiological comparison.

Lactate thresholds, maximal lactate steady state (MLSS) and exercise-intensity domain boundaries have distinct definitions and testing procedures (Jamnick et al., 2020). Blood lactate reflects production, exchange and utilization across tissues; concentration alone identifies neither oxygen deprivation nor a direct cause of fatigue (Brooks, 2018). A sweat-workload association must therefore specify whether its target is sweat concentration, blood concentration, threshold timing, threshold workload or post-exercise recovery.

During intermittent exercise, collection and electrode response can outlast a work-recovery interval. A recovery reading may contain liquid collected during work, and a reading in the next effort may contain liquid from before that effort. Local gland metabolism and changes in secretion additionally alter concentration. Determining the chemical meaning of the value and determining its collection interval are separate measurement tasks.

Van Hoovels et al. examined sweat-blood relationships and the practical constraints of lactate sensing (Van Hoovels et al., 2021); Derbyshire et al. evaluated lactate in human sweat (Derbyshire et al., 2012). Sonner et al. described

gland and duct transport (Sonner et al., 2015), while Ursem et al. examined microfluidic flow measurement (Ursem et al., 2025). The analysis here connects those physiological and fluidic constraints to alternating exercise intervals. It derives collector-entry time from cumulative liquid displacement and relates reservoir carryover to a concentration-error tolerance.

HUMAN MEASUREMENTS: CONCENTRATION, THRESHOLDS AND PREDICTION

LOCAL DELIVERY AND CIRCULATORY INTERPRETATION

Eccrine-gland metabolism and collection conditions influence sweat lactate (Baker and Wolfe, 2020; Baker, 2019). Attachment over a working muscle does not identify a direct pathway from that muscle to the electrode. Regional differences in gland density and secretion make anatomical placement part of the measurement definition (Taylor and Machado-Moreira, 2013).

Let $Q(t)$ be volumetric flow through the collector inlet and $C_{in}(t)$ the concentration entering at that time. Lactate delivery is

$$J_L(t) = Q(t)C_{in}(t). \quad (1)$$

For Q in $\mu\text{L min}^{-1}$ and concentration in mmol L^{-1} , J_L has units of nmol min^{-1} . Measuring both variables distinguishes a concentration change from a change in local delivery. For example, a falling concentration can accompany unchanged delivery if water flow rises sufficiently. This comparison supports investigation of dilution; it does not establish tissue origin or whole-body lactate clearance.

To examine whether concentration and flow can separate local glandular production from transfer through the circulation, write the inlet delivery as

$$J_L(t) = J_{\text{local}}(t) + J_{\text{exchange}}(t). \quad (2)$$

Here J_{local} and J_{exchange} are nonnegative contributions to delivery at the collector inlet. Neither term is measured separately by the electrode. An admissible function $h(t)$ can be added to one term and subtracted from the other while leaving total delivery unchanged. Eq. (2) therefore leaves the partition undetermined unless an additional physiological relation constrains it. Blood-lactate prediction can nevertheless be tested empirically using other variables and independent athletes; such prediction need not identify the two contributions.

The flow required by Eq. (1) belongs to the chemical sensing path. A nearby ventilated capsule measures local sweating under its own area and boundary conditions. Scaling that rate to a patch assumes uniform secretion, complete capture and compatible occlusion and pressure. Regional flow can be a useful predictor, but it is not automatically a measurement of liquid displacement through the collector.

The integrated Xuan device yielded a thigh sweat-blood correlation of $r = 0.813$ from 27 observations after excluding sweat concentrations $\geq 20 \text{ mmol L}^{-1}$ (Xuan et al., 2023). The separate Analysis & Sensing investigation pooled 85 observations, mainly from the forehead, without a blood-sweat correlation (Xuan et al., 2023). Placement, concentration exclusions and repeated observations differ between these comparisons. Ion-chromatography comparisons test the electrode against an independent sweat assay; blood comparisons test a different endpoint. Neither a nonsignificant mean assay difference nor a high correlation defines the individual concentration-error distribution.

For Maeda et al.'s 40 men, define $\Delta t = t_{sLT} - t_{bLT}$, so that a positive value indicates a later sweat threshold. The mean difference was $+19.3 \text{ s}$, the individual agreement limits were -126.2 to $+164.7 \text{ s}$, and five late-sweating participants had a mean difference of $+106.8 \text{ s}$ (Maeda et al., 2023). The 95% confidence interval of the overall mean was -4.8 to 43.3 s . That interval describes average bias, whereas the agreement limits describe the spread of individual differences. Differences exceeding two minutes can cross a short work-recovery boundary even when average bias is small.

Okawara et al. determined sweat thresholds in 20 of 24 swimmers during interrupted testing; rest suppressed perspiration sufficiently to prevent determination in four participants (Okawara et al., 2024). Thus threshold availability was 83.3% in that protocol. The 20 successful determinations yielded a threshold-speed correlation of $r = 0.824$. Continuous testing yielded sweat thresholds in all 24 participants, but the comparison with blood threshold used interrupted testing on a different day. Detection frequency and between-day variation must accompany interpretation of the correlations.

Rabost-Garcia et al. combined sweat variables, heart rate and participant characteristics in 152 observations from 32 adults (Rabost-Garcia et al., 2023). RMSE decreased from 2.33 to 1.56 mmol L^{-1} after exclusion of high blood-lactate values, narrowing the concentration range being predicted. An 80:20 split and a trajectory from one participant excluded from training do not quantify error across independent athletes performing successive sprints. Subtracting a blood-meter RMSE from model RMSE does not isolate additional wearable error; reference variance and covariance are also required. Hattori and Yashiro fitted recovery records from five runners, obtaining $R^2 = 0.763$, RMSE 1.612 and MAE $0.995 \text{ mmol L}^{-1}$ without an independent validation dataset (Hattori and Yashiro, 2025). Fitted blood trajectories and serial dependence limit interpretation of that development fit.

LIQUID TRANSIT AND RESIDUAL CONCENTRATION ERROR

INLET TIME UNDER VARIABLE FLOW

A complete timing account distinguishes gland secretion, emergence at the skin, entry into the collection path, arrival at the electrode and electronic acquisition. Duct transit and skin-interface storage precede collector entry; electrode kinetics and signal filtering follow arrival. A collector-only calculation cannot identify glandular secretion time. Throughout the following analysis, $s(t)$ means *collector-inlet entry time*.

Consider an already primed path with fixed upstream liquid volume V_d , incompressible liquid, equal inflow and outflow, no leakage or evaporation, and ideal plug transport without mixing. Material arriving at the sensing position at t entered at $s(t)$, where

$$\int_{s(t)}^t Q(u) du = V_d, \quad \tau_d(t) = t - s(t). \quad (3)$$

The integration includes the displacement history. At constant Q_0 , $\tau_d = V_d/Q_0$; at changing flow, $V_d/Q(t)$ generally fails because it ignores earlier delivery. Before priming, a separate filling calculation is required, and no valid inlet time is assigned until the sensing path contains liquid.

Where $Q(s(t)) > 0$, differentiation gives

$$\frac{ds}{dt} = \frac{Q(t)}{Q(s(t))}, \quad \frac{d\tau_d}{dt} = 1 - \frac{Q(t)}{Q(s(t))}. \quad (4)$$

Low current flow relative to the flow at entry stretches a feature on the display timeline. During a zero-flow period, a nonreactive ideal sample does not advance, even if electronics continue recording. If entry occurred within a zero-flow plateau, a generalized inverse of cumulative volume can identify an interval rather than a unique timestamp. Evaporation, backflow and variable storage require additional terms; Eq. (4) is not extrapolated through such conditions.

REPLACEMENT FRACTION AND CONCENTRATION TOLERANCE

For a separate, perfectly mixed reservoir of constant volume V_m , equal inflow and outflow, and negligible lactate consumption or adsorption,

$$V_m \frac{dC_m}{dt} = Q(t) [C_{in}(t) - C_m(t)]. \quad (5)$$

Define cumulative turnovers after t_0 as $\Theta(t) = V_m^{-1} \int_{t_0}^t Q(u) du$. The fraction of material present at t_0 that remains is

$$R(t) = e^{-\Theta(t)}, \quad F(t) = 1 - e^{-\Theta(t)}. \quad (6)$$

Thus one turnover replaces approximately 63.2% and three replace approximately 95.0%. The calculation describes material replacement, not physiological validity. It applies to the mixed limit, not an unmixed channel, a wick or a geometry with stagnant regions.

For a constant inlet step from C_{old} to C_{new} with the reservoir initially at C_{old} , Eq. (5) gives

$$|C_m(t) - C_{new}| = Ae^{-\Theta(t)}, \quad A = |C_{old} - C_{new}|. \quad (7)$$

An allowable residual concentration error $\varepsilon > 0$ therefore requires, for $A > 0$,

$$\Theta(t) \geq \max \left\{ 0, \ln \left(\frac{A}{\varepsilon} \right) \right\}. \quad (8)$$

Selecting 95% replacement means $\Theta \geq -\ln(0.05) = 2.9957$ and limits the residual to 5% of the *step amplitude*. For a 10-mmol L⁻¹ step, that residual is 0.5 mmol L⁻¹; it is not necessarily 5% of the new concentration or of total measurement error. Changes in inlet concentration after the step invalidate a single-step interpretation, although Eq. (5) remains the governing balance under its assumptions.

Transport and electrode responses also need separate identification. A first-order electrode approximation, if experimentally justified, would obey $T_e \dot{C}_e + C_e = C_a$, with C_a the concentration at the electrode and C_e its calibrated response. For a constant step, its own 95% response time is approximately $3T_e$. Serial plug transport, mixing and electrode response combine dynamically; their individual 95% times cannot simply be added and called the complete device's 95% time. A tracer characterizes liquid residence, while lactate steps characterize the additional electrochemical response.

TWO-MINUTE WORK AND RECOVERY INTERVALS

Ursem et al. describe a resettable flow architecture with a $10\text{-}\mu\text{L}$ collection capacity and a tested range of $0.25\text{--}4\text{ }\mu\text{L min}^{-1}$ (Ursem et al., 2025). The calculations below use those volume and flow scales for two separate fluidic limits: a liquid-filled plug path with $V_d = 10\text{ }\mu\text{L}$ and a perfectly mixed reservoir with $V_m = 10\text{ }\mu\text{L}$. Collection capacity does not identify the upstream volume of a lactate electrode. The calculations therefore define transport at this scale without assigning the geometry to a particular lactate device.

The imposed inlet-flow sequence consists of 2 min at $4\text{ }\mu\text{L min}^{-1}$ followed by 2 min at $0.25\text{ }\mu\text{L min}^{-1}$. Repeated cycles start at $t = 0$; flow before $t = 0$ is $4\text{ }\mu\text{L min}^{-1}$, defining the liquid initially occupying the plug path. The higher-flow intervals are labelled work and the lower-flow intervals recovery. These labels locate exercise boundaries; the instantaneous switches are mathematical boundary conditions, not measurements of sweat secretion. With time in minutes,

$$Q(t) = \begin{cases} 4, & t < 0 \text{ or } 0 \leq (t \bmod 4) < 2, \\ 0.25, & 2 \leq (t \bmod 4) < 4. \end{cases} \quad (9)$$

One complete cycle displaces $8.5\text{ }\mu\text{L}$. Material entering at $t = 0$ requires $10\text{ }\mu\text{L}$ of subsequent displacement: 8 during the first work interval, 0.5 during recovery and 1.5 during the next effort. Arrival is therefore $t = 4 + 1.5/4 = 4.375\text{ min}$, after the second effort has started. At $t = 4\text{ min}$, the inlet time assigned to the current plug sample is $s = -0.375\text{ min}$, not the current bout. For $V_d = 1\text{ }\mu\text{L}$ under the same flow, the first-onset material arrives at 0.25 min . Reducing the path volume from 10 to $1\text{ }\mu\text{L}$ therefore reduces the first-onset transit time from 4.375 to 0.25 min under the same boundary conditions.

The separate $10\text{-}\mu\text{L}$ reservoir retains $e^{-0.8} = 44.93\%$ of the material present at $t = 0$ after the first work interval and $e^{-2.55} = 7.81\%$ after three complete cycles (12 min). It reaches 95% replacement after $29.957\text{ }\mu\text{L}$ of displacement, at approximately 13.114 min , during the fourth work interval. Constant flow at $4\text{ }\mu\text{L min}^{-1}$ would reach the same fraction at 7.489 min . Figure 1 gives the flow, inlet-time mapping and reservoir-replacement history. The work labels describe interval timing rather than glandular lactate production.

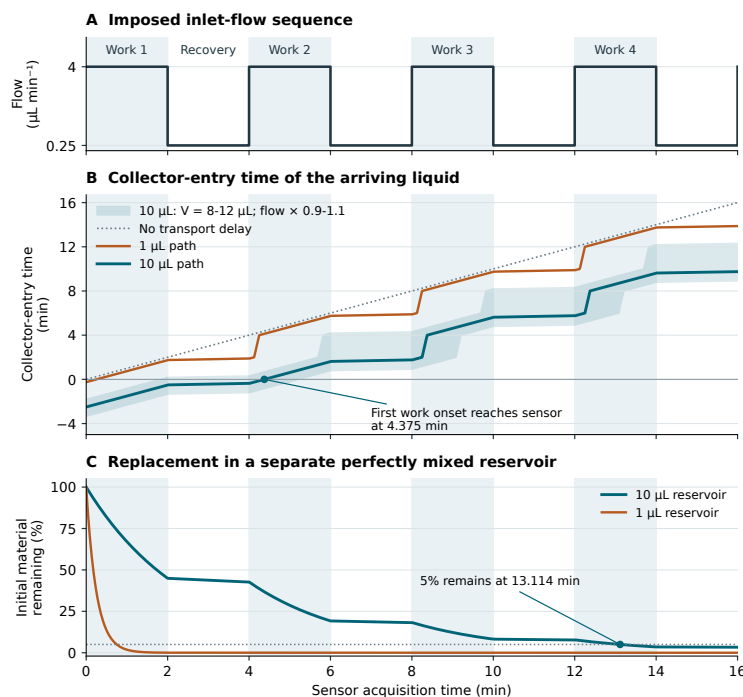


FIGURE 1. COLLECTOR-ENTRY TIME AND RESERVOIR CARRYOVER CALCULATED FROM EQS. (3), (6) AND (9). WORK INTERVALS ARE SHADED; RECOVERY INTERVALS ARE UNSHADED. (A) IMPOSED FLOW IS $4\text{ }\mu\text{L min}^{-1}$ DURING EACH 2-MIN WORK INTERVAL AND 0.25 DURING EACH 2-MIN RECOVERY INTERVAL. (B) COLLECTOR-ENTRY TIMES FOR IDEAL PRIMED PLUG PATHS OF 1 AND $10\text{ }\mu\text{L}$; THE DOTTED DIAGONAL INDICATES ZERO TRANSPORT DELAY. FOR THE $10\text{-}\mu\text{L}$ PATH, SHADING BOUNDS VOLUMES OF $8\text{--}12\text{ }\mu\text{L}$ AND FLOW MULTIPLIERS OF $0.9\text{--}1.1$; IT IS A DETERMINISTIC SENSITIVITY INTERVAL. (C) INITIAL-MATERIAL FRACTIONS FOR SEPARATE IDEAL MIXED RESERVOIRS. THE $10\text{-}\mu\text{L}$ RESERVOIR CROSSES THE 5% LINE AT 13.114 min . CURVES REPRESENT THE DEFINED PLUG AND MIXED-RESERVOIR SYSTEMS; THEY CONTAIN NO PARTICIPANT MEASUREMENTS.

Sensitivity to path volume and flow is evaluated over $V = 8\text{--}12\text{ }\mu\text{L}$ and a multiplier $k = 0.9\text{--}1.1$ applied to the entire inlet-flow sequence. The equivalent displacement V/k ranges from 7.273 to $13.333\text{ }\mu\text{L}$. Liquid entering at the first work onset consequently reaches the sensing position between 1.818 and 5.208 min , spanning the first and second efforts. This bounded calculation shows how volume and flow errors can change interval assignment. It is not a confidence interval. Estimating a device-specific interval requires measured geometry, time-varying flow error and a residence-time distribution.

DEVICE-SPECIFIC TIMING AND EXERCISE VALIDATION

Sequential reservoirs and capillary bursting valves retain collection order, although the time covered by each fraction depends on flow (Choi et al., 2017). Regional patches measure local flow and chemistry (Nyein et al., 2019); Komkova et al. distinguish a flow-independent lactate-concentration response from a flow-sensitive response (Komkova et al., 2022). Relating either signal to transport requires flow through the lactate-sensing path and the same liquid interval.

Table 1 identifies device quantities that affect temporal interpretation. Xuan et al.'s integrated device has a batch $t_{95} < 80$ s, while its abstract states a response below 90 s (Xuan et al., 2023). Both concern response characterization; neither includes the complete transit from skin to display during interrupted sweating. Bubble-tolerant microfluidics, osmotic extraction and induced sweating address fluid availability or handling (Shitanda et al., 2023; Saha et al., 2022; Emaminejad et al., 2017). Their physiological interpretation additionally depends on whether the collected liquid represents spontaneous exercise sweating.

TABLE 1. LACTATE-DEVICE SPECIFICATIONS AND FLOW-SENSING QUANTITIES RELEVANT TO TEMPORAL INTERPRETATION. EACH ROW RETAINS THE APPARATUS AND CONDITIONS OF ITS CITED INVESTIGATION.

Arrangement	Device quantity	Timing determination
Integrated lactate device (Xuan et al., 2023)	Lactate range 1–20 mmol L ⁻¹ ; flow perturbation 0–12.5 $\mu\text{L min}^{-1}$; pre-test calibration at 5 $\mu\text{L min}^{-1}$; batch $t_{95} < 80$ s.	Determine priming and upstream volume, on-body flow and the combined liquid/electrode response during pauses.
Multiparametric collection (Rabost-Garcia et al., 2023)	Separate flow channel volume 24.3 μL ; 4-mm inlet diameter; collection zone refilled in less than 3 min after cleaning in the tested arrangement.	Determine the interval captured by each lactate sample; the flow channel's total capacity is not the lactate sampling path's upstream volume.
Recovery sensing (Hattori and Yashiro, 2025)	Sweat sensor range 0–5 mmol L ⁻¹ ; 1-Hz acquisition; adjacent ventilated capsule measures regional sweat rate.	Establish actual liquid flow and refresh at the lactate sensor rather than inferring them from adjacent skin.
Resettable flow architecture in Ursem et al. (2025)	Collection capacity 10 μL ; tested range 0.25–4 $\mu\text{L min}^{-1}$.	Identify sensing-path dead volume and effects of resetting. Capacity supplies a calculation scale, not a validated lactate latency.

CHEMICAL CALIBRATION, TIME ALIGNMENT AND EXTERNAL TESTING

Chemical calibration requires an independent sweat assay across the intended concentration, temperature and pH ranges, with an acceptable error defined in mmol L⁻¹. Lactate steps at constant flow determine chemical response; flow changes at constant concentration determine hydrodynamic sensitivity. Alternating flow and no-flow intervals establish whether a continuing display is receiving new liquid. Nonreactive tracers determine priming, transit and residence-time distributions. These are device-validation procedures; the present transport analysis evaluates the equations under specified boundary conditions.

On-body testing should synchronize exercise boundaries, collection geometry, actual flow, calibration and valid-sample decisions. A timed assay of sweat accumulated between inlet times a and b represents

$$\bar{C}_{\text{vol}} = \frac{\int_a^b Q(u)C_{\text{in}}(u) du}{\int_a^b Q(u) du}, \quad \int_a^b Q(u) du > 0. \quad (10)$$

It is a volume-weighted mean, not necessarily the unweighted mean of electronically timestamped sensor values. For plug flow, sensor concentration must first be assigned to $s(t)$ and paired with $Q(s(t))$. For mixing, estimating inlet concentration requires inversion of Eq. (5), amplifying derivative noise and becoming poorly conditioned at low flow. A missing or unresolved interval should remain distinguishable from a model-based prediction.

For physiological testing, concentration agreement should be expressed in mmol L⁻¹, with bias, prediction error and participant-level uncertainty. Threshold testing should define its algorithm and quantify signed and absolute differences, individual limits of agreement, proportional error and missing detections. A timing confidence interval for average bias is insufficient to assign individual bouts. Acceptance limits should follow the intended decision and interval duration rather than a universal correlation cutoff.

Model evaluation must separate athletes or complete sessions. Random separation of adjacent readings can place the same physiological trajectory in development and test sets. Held-out athletes assess population transfer; held-out sessions assess repeat-use performance. Reference uncertainty, including blood-trajectory fitting, should propagate into prediction intervals. Training and test ranges and every excluded observation should be specified. Sex, fitness, sweating variability, site, thermal conditions and recovery duration should be represented in the intended population; sample size should address the precision of the stated agreement endpoint, not the number of electronic readings.

INTERVAL ASSIGNMENT AND EXERCISE PRESCRIPTION

A bout-specific test must determine whether an estimated physiological quantity belongs to the correct work–recovery interval. Repeated efforts with different recovery durations allow calculation of valid-sample coverage and the proportion of readings assigned to the wrong interval. If the collector–entry interval crosses an exercise boundary, assignment remains unresolved. Carrying the preceding value forward cannot create a new sample. An independently validated physiological estimate can be displayed with its prediction interval and measurement status.

Muramoto et al. tested 30-min constant workloads after measuring sweat threshold (Muramoto et al., 2023). MLSS occurred at 110, 115, 120 and 125% of sweat-threshold workload in 1, 4, 3 and 7 of the 15 participants, respectively. Testing stopped at 125%, and the relation varied with training habits. Sweat threshold therefore did not provide one universal MLSS workload multiplier. Likewise, a graded-exercise threshold comparison cannot determine the metabolic contribution or recovery kinetics of adjacent sprints.

INTERPRETIVE LIMITS AND CONCLUSIONS

The nine investigations differ in participant coverage, collection site, exercise protocol and comparison endpoint. Their correlations, mean-bias confidence intervals, individual agreement limits and prediction errors cannot be combined into a single accuracy estimate. Four missing swimmer thresholds, concentration exclusions in the Xuan and Rabost-Garcia analyses, and the five-runner development fit illustrate different restrictions on availability and transfer. The targeted article selection does not establish exhaustive coverage or a ranking of commercial devices.

Plug transport and perfect mixing are separate fluidic limits. Dispersion, stagnant regions, adsorption, evaporation, pressure-dependent storage and electrode kinetics can alter a physical collector's response. Under the flow sequence analysed here, a 10- μ L plug path delays first-onset liquid until 4.375 min, whereas a 10- μ L mixed reservoir requires 13.114 min for 95% replacement. The volume and flow bounds place first arrival between 1.818 and 5.208 min. These times follow the imposed boundary conditions; they do not measure sweat secretion or calibrate sweat concentration to blood.

Sweat-lactate timing during intermittent exercise depends on cumulative delivery as well as electrode response. Individual interpretation requires collector–entry timing and independent validation of the physiological quantity being estimated. Maeda et al.'s -126.2 to $+164.7$ s agreement limits show why mean timing bias is insufficient, while the swimming results show why detection frequency must accompany threshold correlation. A displayed value should carry an inlet-time interval and, when blood lactate is estimated, a prediction interval established in independent athletes or sessions.

DECLARATIONS

CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this study.

DATA AVAILABILITY

No dataset was used for this research.

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