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Toward Real-Time Organism-Level Monitoring of Photobiomodulation Response

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Abstract: Photobiomodulation (PBM) is increasingly discussed across dentistry, orofacial pain, rehabilitation, wound care, and other translational clinical settings. Current PBM literature appropriately emphasizes optical parameters, tissue optics, mitochondrial and redox signaling, inflammatory modulation, and local clinical outcomes [1-3]. These foundations remain essential. A complementary question remains less developed: what occurs at the level of the patient during PBM care?

Two patients may receive similar wavelengths, irradiance, fluence, anatomical targeting, and exposure duration. They may still differ in breathing rhythm, muscular guarding, cardiovascular variability, movement, and behavioral regulation during the same clinical encounter.

This Perspective proposes that PBM research may benefit from a real-time physiological observation layer at the patient level. The article presents a restrained framework for observing short-term heart rate variability (HRV), respiratory rhythm, respiratory heart rate variability patterns, waveform quality, movement, posture, and behavioral context before, during, and after PBM exposure.

The discussion emphasizes biphasic dose-response behavior, hormesis, nonlinear adaptation, and interindividual physiological variability. HRV is not presented as an exposure-selection tool, diagnostic method, treatment endpoint, or proof of effectiveness. Instead, patient-level monitoring is framed as a complementary observational layer that may help contextualize tissue-level outcomes and patient-reported responses.

Respiratory confounding, LF/HF limitations, placebo and context effects, wearable-device constraints, and the need for ethics-approved prospective studies remain central. If investigated carefully, this framework may help PBM research describe dynamic treatment-response patterns within a broader systems-physiology context.

Keywords: photobiomodulation; heart rate variability; respiratory heart rate variability; dentistry; biphasic dose response; hormesis; physiological monitoring; systems physiology; pain; clinical translation.

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1. INTRODUCTION

Photobiomodulation (PBM) describes the application of non-ionizing red or near-infrared light to biological tissues with the intention of influencing cellular and tissue processes without a primary ablative or thermal effect [1-3]. In dentistry,

PBM has been discussed in relation to oral mucositis, temporomandibular disorders, periodontal therapy, endodontic pain, implantology, orthodontics, dentin hypersensitivity, and postsurgical recovery [4]. Its broader clinical footprint now extends into rehabilitation, pain science, sports medicine, neurology, and wound care. In these settings, symptom change,

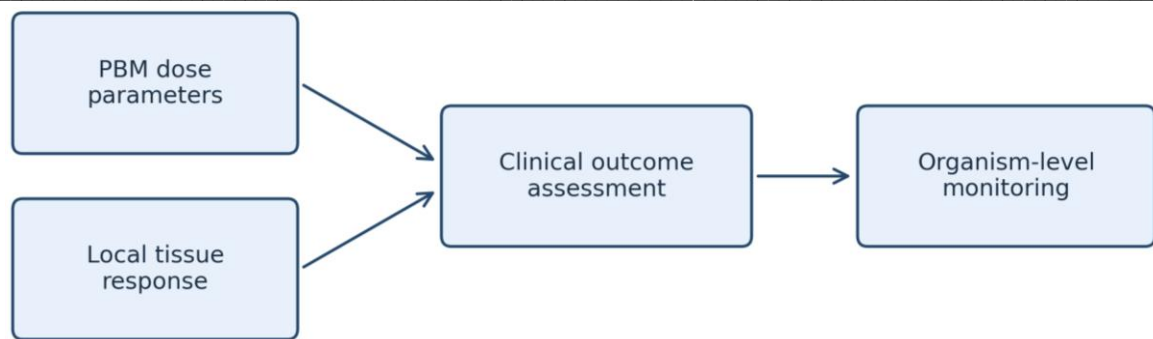


Fig. (1). Conceptual model of PBM response assessment. The established tissue-level pathway and exploratory organism-level observation pathway are complementary. The organism-level stream is observational and hypothesis-generating.

movement behavior, and physiological regulation often evolve together. The appeal is clear: PBM is non-invasive, mechanistically plausible, and clinically adaptable. The caution is also clear: protocol heterogeneity, variable evidence quality, and inconsistent reporting remain major limitations [1-3].

Most PBM measurement frameworks are built, appropriately, around the intervention and the illuminated tissue. Investigators report wavelength, power, irradiance, fluence, exposure time, pulse structure, spot size, anatomical target, and treatment frequency. Outcomes are then assessed through pain ratings, edema, tissue repair, oral function, mouth opening, mobility, or recovery time. This architecture is indispensable. Without accurate dosimetry and meaningful clinical outcomes, PBM cannot become a reproducible clinical science. Fig. (1) summarizes the proposed relationship between established PBM assessment streams and the additional patient-level observation layer.

Yet a clinical intervention is not received by an isolated tissue compartment. It is received by a person who breathes, anticipates, guards, moves, attends, relaxes, startles, swallows, and adapts. A patient undergoing PBM for orofacial pain may alter mandibular muscle tone, respiratory cadence, facial tension, head posture, and swallowing frequency during the appointment. A rehabilitation patient may become stiller and more settled, or may become more restless. These observations do not prove a PBM effect. They do show that PBM occurs within a wider regulatory context.

The central thesis of this Perspective is deliberately focused: PBM research may be missing a real-time patient-level physiological observation layer. Such a layer would not replace tissue-level mechanisms, dosimetry, or patient-centered outcomes. It would sit beside them. Its purpose would be to ask whether short-term physiological patterning during care is observable, repeatable, and potentially informative. HRV, respiratory rhythm, respiratory heart rate variability patterns, waveform quality, movement, posture, and behavioral context are candidate variables for this purpose, provided that they are interpreted conservatively [5-7].

For practical discussion, this article uses the term rapid HRV observation sequence as a working label for a structured

observation sequence. It is not intended to denote a commercial product, proprietary device, diagnostic method, dosing method, or measure of treatment success. In this manuscript, the phrase simply refers to a rapid and disciplined way of asking three questions: Are the physiological signals interpretable? Have breathing and artifact been considered? Is the pattern worth documenting for future study?

2. WHY AN ORGANISM-LEVEL OBSERVATION LAYER MAY MATTER

PBM mechanisms are commonly described through mitochondrial chromophores, cytochrome c oxidase activity, adenosine triphosphate production, nitric oxide signaling, redox-sensitive transcription, inflammatory mediator modulation, and downstream tissue repair pathways [1-3]. These mechanisms explain why local tissue response remains central to PBM science. They do not fully describe the treatment session as a physiological event occurring within a living person.

The patient's short-term state can change quickly. Breathing may slow when an appointment feels less threatening. Jaw guarding may ease as the patient becomes more settled. Pulse-derived waveforms may become cleaner because the hand is still, not because physiology has meaningfully changed. HRV may increase during quiet rest or slow breathing even when the local tissue response remains unknown. Conversely, pain, worry, movement, swallowing, sensor instability, or procedural interruption may obscure any physiological trend. These realities make real-time monitoring potentially informative, but also vulnerable to overinterpretation.

Observation must be separated from attribution. Observing a change in respiratory heart rate variability patterns during PBM is not the same as proving that PBM caused the change. Observing reduced movement or less visible guarding does not establish tissue repair. The value of this additional layer is more modest and more defensible. It may improve description of the clinical encounter, identify recordings that should not be interpreted, and generate better research questions (Table 1).

In dentistry, this issue has direct translational relevance. Dental care often evokes anticipatory arousal, altered breathing, facial muscle activation, swallowing, gag sensitivity, and

Table 1. Complementary PBM assessment layers and organism-level questions.

Assessment Layer	Established PBM Emphasis	Primary Contribution	Additional Organism-Level Question
Delivered parameters	Wavelength, irradiance, fluence, exposure time, pulse structure, spot size, treatment frequency	Supports reproducibility and protocol comparison	What was the patient's physiological state during light delivery?
Tissue mechanisms	Mitochondrial signaling, nitric oxide, redox biology, inflammatory modulation	Provides biological plausibility	Did respiratory, cardiovascular, behavioral, or neuromuscular patterning change during the session?
Clinical outcomes	Pain, edema, wound healing, oral function, range of motion, recovery time	Determines patient-centered relevance	Were immediate session dynamics documented alongside later outcomes?
Biomarkers and imaging	Cytokines, oxidative stress markers, perfusion, tissue imaging	Deepens mechanistic interpretation	Can short-term physiological observation complement less feasible biomarker approaches?
Follow-up assessment	Hours, days, or weeks after treatment	Evaluates durability and clinical meaning	Were immediate adaptation patterns lost because they were never observed?

jaw protection. These features can influence HRV and waveform quality before any conclusion is drawn about PBM itself. In temporomandibular, endodontic, periodontal, implant, orthodontic, and postsurgical contexts, the illuminated target may be anatomically specific. The patient's wider physiological state may still shape the appointment as a whole. The same logic extends to musculoskeletal pain, rehabilitation, postoperative recovery, and other settings where physiology and behavior are inseparable.

3. BIPHASIC RESPONSE, HORMESIS, AND INTERINDIVIDUAL VARIABILITY

The biphasic dose-response literature is one reason to avoid a linear or purely parameter-centered interpretation of PBM. PBM effects are often described as dose-sensitive and nonlinear. Insufficient exposure may produce little measurable response. An intermediate range may be associated with adaptive biological effects. Excessive exposure may reduce benefit or produce inhibitory responses [8-10]. This pattern is commonly discussed in relation to hormesis, in which a limited biological stimulus may support adaptation while a greater stimulus may be neutral or unfavorable.

This concept does not mean that every PBM response can be mapped onto a universal curve. Living systems are not passive receivers of dose. They are adaptive networks influenced by tissue condition, vascularity, inflammation, sleep, stress physiology, respiratory pattern, and behavioral context. A parameter set tolerated well in one individual may coincide with a different patient-level pattern in another. Even within the same patient, a session after poor sleep, acute stress, or heightened pain may differ from a session under calmer conditions.

The clinical implication is not that HRV should be used to choose PBM exposure. It should not. PBM dosimetry requires optical, tissue, device, and indication-specific knowledge that HRV cannot replace. Rather, biphasic and hormetic concepts make a subtler point: identical PBM parameters may occur

alongside different short-term physiological patterns. One patient may breathe regularly, remain still, and show stable respiratory-related heart-rate variation. Another may show breath holding, jaw guarding, repeated movement, and noisy pulse waveforms. These patterns do not rank treatment success. They describe physiological context (Table 2).

This section is therefore a rationale for better observation, not a claim of biological control. The aim is to move PBM research toward a richer description of response dynamics while preserving a clear distinction between delivered dose, tissue effect, symptom outcome, and patient-level physiological state.

4. HRV, BREATHING, AND WAVEFORM ORGANIZATION

HRV refers to variation in the time intervals between successive heartbeats. It is usually measured from normal-to-normal intervals in electrocardiographic recordings or estimated from pulse-derived signals [5, 6]. HRV can be summarized using time-domain, frequency-domain, and nonlinear methods. It is physiologically interesting because it reflects aspects of cardiovascular regulation. It is also easily misused. Foundational standards and later reviews emphasize that HRV depends on recording length, posture, age, health status, medication use, sleep, activity, respiratory pattern, analysis method, and signal quality [5-7].

Breathing is especially important. Respiratory-related heart-rate variation has traditionally been called respiratory sinus arrhythmia. A recent international Expert Recommendation proposes the term respiratory heart rate variability to clarify that breathing contributes to heart-rate variation across traditional HRV bands. The same recommendation cautions that its amplitude should not be treated as a simple measure of vagal tone [11]. Heart rate commonly accelerates during inspiration and decelerates during expiration. However, this relationship is influenced by vagal activity, respiratory drive,

Table 2. Conceptual rationale for organism-level observation and essential interpretive boundaries.

Concept	Relevance to PBM Science	Possible value of Organism-Level Observation	Essential Boundary
Biphasic dose response	PBM response may differ across insufficient, intermediate, and excessive exposure ranges	Encourages documentation of whether short-term physiological patterns vary across sessions or individuals	HRV must not determine PBM exposure
Hormesis	Adaptive effects may occur within limited biological ranges	Draws attention to adaptive versus unsettled session patterns	Adaptation cannot be inferred from a single HRV value
Nonlinear adaptation	Small contextual changes may alter respiratory, cardiovascular, and behavioral signals	Supports repeated within-person observation rather than isolated readings	Nonlinear patterning does not establish PBM efficacy
Interindividual variability	Similar PBM parameters may coexist with different patient-level responses	Encourages documentation of state, breathing, guarding, posture, and artifact	Differences do not automatically imply better or worse treatment
State dependence	Pain, sleep, anxiety, medication, and recent exertion can influence recordings	Helps interpret why one session differs from another	Contextual explanation must remain visible

Table 3. Candidate monitoring domains, their value, and required restraint.

Monitoring Domain	What is Observed	Why it Matters	Required Restraint
HRV trend	Directional pre/post change across comparable short windows	May describe short-term regulatory patterning	Does not diagnose dysfunction or establish PBM response
Breathing rhythm	Rate, regularity, pauses, sighing, breath holding, effort	Strongly shapes respiratory heart rate variability	Must be documented before HRV trends are interpreted
Waveform quality	Sensor contact, ectopy, pulse morphology, motion artifact	Determines whether data are usable	Poor signal should be reported rather than forced into meaning
Movement and guarding	Jaw tension, facial movement, posture shift, swallowing	Provides chairside context for signal changes	May reflect comfort, anxiety, instruction, or environment
Respiratory heart rate variability pattern	Relationship between breathing and heart-rate oscillation	May indicate organized cardiorespiratory patterning	Coupling may arise from breathing change alone

posture, metabolic state, and measurement context [11, 12]. In practical terms, an HRV change observed during PBM is difficult to interpret unless breathing rhythm and signal quality have been documented.

Waveform organization can add useful discipline. A clinician-scientist reviewing a real-time tracing may ask whether the interbeat interval series is stable, whether the pulse waveform is clean, whether breathing is regular, whether movement artifact is present, and whether pre/post windows are comparable. This attention prevents a common error: trusting a summary number when the underlying signal is poor.

The LF/HF ratio requires particular caution. Although historically used as an index of sympathovagal balance, this interpretation has been strongly criticized because LF and HF power do not map cleanly onto sympathetic and parasympathetic activity [5, 13]. LF/HF is influenced by breathing, baroreflex function, posture, recording conditions, and analytic choices. In a PBM monitoring framework, LF/HF may be reported descriptively in research. It should not guide chairside decisions or be treated as evidence of autonomic correction (Table 3).

5. A PRACTICAL FRAMEWORK FOR PBM SESSIONS

A clinically useful framework should be simple enough for chairside feasibility and conservative enough for scientific credibility. The proposed rapid HRV observation sequence has three windows: a short pre-PBM baseline, an intra-PBM observation period, and a post-PBM review window. Fig. (2) outlines this three-window workflow. Each window should be recorded under comparable posture and environmental conditions whenever possible. Minimum documentation should include PBM parameters, patient position, breathing context, movement or artifact, sensor type, recording duration, and relevant confounders such as caffeine, pain flare, medication changes, acute anxiety, or recent exertion.

The framework is not a score. It is a disciplined sequence of questions. Was the recording technically interpretable? Was breathing regular or irregular? Did movement artifact dominate the tracing? Were the pre/post windows comparable? Did the patient visibly guard less, move more, breathe differently, or become more settled? Does the pattern warrant

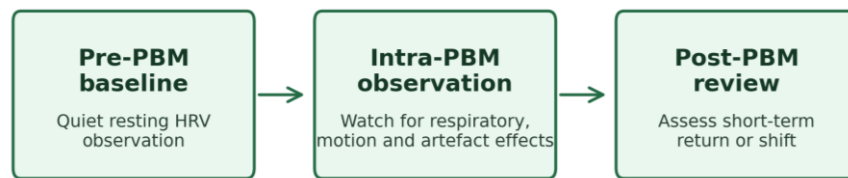


Fig. (2). Proposed three-window monitoring workflow. Comparable pre-PBM, intra-PBM, and post-PBM windows document physiological context without treating HRV or respiratory pattern as proof of efficacy, healing, diagnosis, or exposure adequacy.

Table 4. Practical observation steps and publication-ready documentation language.

Observation Step	Practical Question	Publication-Ready Documentation Language
Baseline	Is the patient still, positioned consistently, and suitable for a short recording?	"A seated baseline was obtained; respiratory rhythm was irregular and brief movement artifact was present."
PBM delivery	Are treatment parameters and clinical context documented?	"PBM was delivered using recorded parameters; the patient remained seated and conversation was minimized."
Respiratory review	Did breathing rate, regularity, sighing, or breath holding change?	"Breathing appeared slower during the observation window, which may influence HRV interpretation."
Signal-quality review	Is the waveform technically interpretable?	"Pulse waveform quality was adequate for trend observation, although swallowing artifacts limited precision."
Pre/post comparison	Are comparable windows available?	"A more regular respiratory-linked oscillation was observed post-session; attribution remains uncertain."
Research decision	Is repeat observation justified?	"The pattern is exploratory and should be tested under standardized observational conditions."

repeated observation under standardized conditions? (see Table 4).

A hypothetical example may clarify the intended tone. A patient receiving PBM as an adjunctive component of orofacial pain care sits quietly during a short pre-session baseline. The tracing shows irregular breathing, intermittent jaw clenching, and motion artifact. During treatment, conversation is reduced. Breathing becomes slower and less erratic; visible mandibular guarding decreases; the pulse waveform becomes cleaner. The post-session pain score is unchanged. This observation does not show that PBM reduced pain or changed autonomic function. It does suggest that the session included a measurable shift in respiratory-behavioral organization that could be documented and, if repeated, studied more formally.

The example is intentionally modest. Clinicians often notice changes in stillness, breathing, facial tone, or guarding during treatment. The challenge is to document these observations without converting them into efficacy claims. A framework that records both physiology and context may help move chairside impressions from anecdote toward researchable questions.

6. CLINICAL TRANSLATION WITHOUT COMMERCIAL OVERREACH

For the Journal of Clinical Dentistry readership, the translational question is practical: could real-time patient-level monitoring improve how clinicians and researchers describe PBM sessions? The answer is not yet known. Still, the question is worth asking because dentistry often sits at the

intersection of tissue intervention, pain, arousal, breathing, and motor behavior.

In dental settings, monitoring may be most relevant where symptoms, procedural expectation, and neuromuscular regulation interact. Orofacial pain, temporomandibular disorders, postoperative discomfort, endodontic pain, periodontal or implant procedures, and orthodontic discomfort are plausible contexts. In these situations, patients may alter breathing, facial tone, swallowing, and mandibular guarding during care [4]. Pain-related physiological monitoring literature supports the broader point that pain is expressed through self-report, behavior, and autonomic-respiratory signals. It also warns against treating physiological signals as sole measures of pain [14, 15]. These changes can affect HRV and pulse waveforms independently of PBM. Recording them may therefore improve interpretation rather than complicate it.

The same framework could apply outside dentistry. Rehabilitation and pain-care environments often involve movement fear, guarding, respiratory dysregulation, and fluctuating autonomic arousal. PBM research in those settings may benefit from documenting whether the patient becomes more settled, more mobile, more guarded, or more physiologically irregular during and after treatment. The clinical value is not in converting these signs into a score. It is in preserving the texture of the treatment encounter for later analysis. These are observations, not endpoints.

Device choice matters. Research-grade electrocardiography remains preferable for precise HRV analysis. Some wearable and pulse-based systems may support practical observation, but validity varies by device, metric, algorithm,

Table 5. Examples of overstated and appropriately restrained interpretation.

Interpretive Risk	Overstated Wording to Avoid	More Appropriate Formulation
Diagnostic inflation	“HRV revealed autonomic dysfunction.”	“The HRV pattern was atypical in this recording and requires cautious interpretation.”
Efficacy overreach	“The waveform demonstrated a PBM response.”	“The pre/post trend may represent an exploratory physiological pattern.”
Dose inference	“HRV identified the preferred PBM exposure.”	“HRV was observed alongside documented PBM parameters; exposure decisions require separate evidence.”
Airway inference	“Breathing irregularity established airway dysfunction.”	“Breathing irregularity was observed and should be evaluated clinically only if independently indicated.”
Device certainty	“The wearable score was the clinical endpoint.”	“Device-derived data were treated as supportive observations requiring validation.”

setting, and motion burden [16]. Consumer-derived scores should not be treated as clinical outcomes. If wearables are used, investigators should report device model, sampling method, artifact handling, recording posture, and whether the metric has been validated for the intended context.

7. INTERPRETIVE BOUNDARIES AND RISKS OF OVERSTATEMENT

The credibility of this proposal depends on its safeguards. A single short HRV recording cannot make disease determinations, establish airway status, demonstrate tissue repair, establish treatment response, or show that PBM parameters were appropriate. A more regular waveform may reflect slower breathing, improved sensor contact, less movement, quieter surroundings, patient expectation, or simple rest. These explanations are not nuisances. They are part of the physiology of the clinical encounter.

Placebo and context effects must also be handled honestly. PBM sessions include clinician attention, device ritual, expectation, positioning, reduced conversation, and time away from normal activity. Any of these can influence breathing, movement, pain reporting, and cardiovascular variability. The presence of context effects does not invalidate monitoring. It means that future studies need control conditions, standardized observation windows, and careful language (Table 5).

The safest language is often the most scientifically useful language. Patient-level monitoring can document what happened during a session, whether signals were interpretable, and whether repeated patterns justify study. It cannot, by itself, explain why those patterns occurred. That limitation should be treated as a strength of the framework rather than a weakness. It keeps the proposal within the boundaries of clinical physiology rather than clinical assertion.

8. FUTURE RESEARCH DIRECTIONS

The next step should be ethics-approved observational research rather than immediate clinical implementation as a definitive method. Early studies could test feasibility in adult dental and pain-care settings. Investigators might collect short pre-PBM, intra-PBM, and post-PBM recordings of ECG-derived HRV or validated pulse-derived intervals, accompanied by respiratory monitoring, artifact annotation,

patient position, symptom ratings, and standardized PBM parameters.

Respiration should be built into protocols from the beginning. Without breathing data, HRV interpretation is fragile. Studies may compare spontaneous breathing with paced breathing, but these approaches answer different questions. Spontaneous breathing is more naturalistic and may better reflect chairside care. Paced breathing improves control, but it also changes the physiology being observed. Both approaches can be valuable if the aim is stated clearly.

Biphasic-response research creates another opportunity. Carefully designed studies could examine whether different PBM parameter ranges are associated with different short-term physiological patterns, while maintaining the clear boundary that HRV is not an exposure-selection method. Repeated within-person designs may be especially informative because they can distinguish day-to-day variability from more reproducible response signatures. Null and uninterpretable recordings should be reported; feasibility and failure modes are part of the evidence.

Collaboration will be necessary. PBM researchers bring light-tissue expertise. Dental clinicians and rehabilitation practitioners bring practical treatment contexts. Physiologists bring cardiorespiratory and autonomic interpretation. Biomedical engineers bring signal-processing and device-validation methods. Pain scientists bring understanding of threat, expectation, movement, and behavior. Together, these disciplines can determine whether patient-level monitoring adds information beyond existing tissue and symptom outcomes.

9. CONCLUSION

PBM research has progressed by studying delivered parameters, tissue interactions, molecular mechanisms, and local clinical outcomes. These foundations should remain central. The proposal advanced here is not to replace them, but to add a complementary layer: real-time observation of the regulated patient receiving PBM.

That layer is scientifically attractive because PBM responses may be nonlinear, context-dependent, and individually variable. It is clinically relevant because patients in dental, pain, and rehabilitation settings often change breathing, movement, guarding, posture, and behavioral regulation

during care. It is also vulnerable to misuse if interpreted too strongly. HRV cannot make disease determinations, determine PBM exposure, establish efficacy, or serve as an independent endpoint. Breathing, artifact, posture, expectation, and device limitations must remain visible in every interpretation.

The most defensible future for this idea is careful, ethics-approved research that places patient-level monitoring alongside tissue-level mechanisms and patient-centered outcomes. If that work is done well, PBM science may gain a more complete language for describing dynamic treatment-response patterns. The illuminated tissue remains essential, but it is never physiologically alone. It belongs to a living organism whose respiratory, cardiovascular, behavioral, and neuromuscular patterns evolve during care.

ETHICS STATEMENT

No new human participant research is presented in this article. No identifiable patient data, clinical recordings, images, or unpublished datasets are included. The hypothetical clinical example is illustrative only and does not represent a real patient, case report, or research finding. Any future prospective observational, interventional, feasibility, or validation study involving human participants would require appropriate HREC/IRB review, informed consent, privacy protection, and data-governance procedures before commencement.

CONFLICT OF INTEREST STATEMENT

The author declares no commercial or financial relationships that could be construed as a potential conflict of interest. The term “rapid HRV observation sequence” is used only as a conceptual observation framework and does not denote a proprietary device, commercial product, diagnostic method, dosing method, or treatment endpoint.

AUTHOR CONTRIBUTIONS

Dr Lynette Wallace contributed to the conception of the manuscript, literature interpretation, drafting, critical revision, and approval of the final version.

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