Bimini

RESEARCH SUMMARY

The Science of Transdermal Oxygen Therapy

Peer-reviewed research, clinical studies, and the mechanism behind nanobubble oxygen delivery

For clinicians, sports scientists, athletic trainers, and facility operators conducting technical diligence.

Bimini Hydrotherapy · Houston, TX

biminihydrotherapy.com

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A note on evidence labelling

This document uses three labels throughout, applied explicitly at the point of each claim:

- ESTABLISHED — supported by peer-reviewed, PubMed-indexed literature. A citation number follows. The reader is encouraged to check every one.
- INFERENCE — mechanistically plausible reasoning that connects established findings to the specific case of nanobubble immersion. Not itself demonstrated. Should be treated as hypothesis.
- COMPANY REPORTED — figures, protocols, or outcomes stated by Bimini Hydrotherapy on its own public materials. Not independently verified by the authors of this document and, where noted, not located in the peer-reviewed literature.

Bimini NanoJet systems are **wellness devices**. Nothing in this document should be read as a claim to treat, cure, mitigate, diagnose, or prevent any disease. Readers with medical conditions should consult a physician, and where a condition falls within an approved indication for hyperbaric oxygen therapy, hyperbaric oxygen therapy is the appropriate referral.

Abstract / Executive Summary

Oxygen delivery to peripheral tissue is constrained not by the oxygen content of arterial blood, which is nearly saturated under normal conditions, but by perfusion and diffusion at the microvascular level. In injured, inflamed, or poorly perfused tissue, the final short distance from capillary to mitochondrion becomes the rate-limiting step ESTABLISHED, 40. This creates a legitimate rationale for delivery routes that bypass pulmonary and haemoglobin-mediated transport.

Three bodies of literature bear on transdermal oxygen delivery, and each supports a narrower claim than is often asserted. First, ultrafine bubbles below one micrometre demonstrably persist in water for durations that classical Epstein-Plesset dissolution theory does not predict, with electrostatic stabilisation at the gas-liquid interface the leading explanation; measured zeta potentials of −30 to −60 mV and modal diameters near 100 nm are typical of well-characterised preparations ESTABLISHED, 1, 2. Second, human skin takes up atmospheric oxygen, and this external supply dominates oxygenation of the outer 0.25–0.40 mm of skin —

but not deeper ESTABLISHED, 24. Third, topical normobaric oxygen applied to open wounds improves healing rates in meta-analysis, with pooled risk ratios of approximately 1.6–1.8 across trials of moderate quality ESTABLISHED, 30, 31, 32.

What the literature does **not** contain, as of this writing, is any PubMed-indexed human trial of oxygen nanobubble water immersion measuring tissue oxygenation through intact skin. Systematic PubMed searches for such a trial returned zero results. Bimini reports a Rice University study of more than 100 collegiate athletes showing 43–46% improvement in recovery and performance metrics and near-infrared spectroscopy muscle oxygen saturation rising from approximately 50% to above 90% COMPANY REPORTED. That study is not indexed in PubMed and could not be independently retrieved. This document treats it accordingly, and devotes a full subsection to the methodological questions a reviewer would raise — most importantly, that warm-water immersion produces cutaneous vasodilation that independently raises near-infrared spectroscopy signal in the superficial tissue the probe interrogates ESTABLISHED, 46, 50.

The honest position is that nanobubble immersion rests on a coherent physical mechanism, a supportive preclinical literature, and a company-reported human dataset that has not been peer-reviewed. That is a reasonable basis for a wellness purchase. It is not a basis for a clinical claim.

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1. The Oxygen Delivery Problem

1.1 Arterial oxygen content is rarely the limiting variable

In a healthy adult breathing room air at sea level, haemoglobin leaves the pulmonary capillaries approximately 97–98% saturated. Because haemoglobin carries the overwhelming majority of blood oxygen, increasing the inspired fraction of oxygen adds relatively little to total arterial oxygen content at normobaric pressure; the increment appears almost entirely as dissolved oxygen in plasma, which is governed by Henry's law and is small at one atmosphere. This is the physiological reason hyperbaric oxygen therapy uses pressure rather than concentration alone: raising ambient pressure to 2.0–3.0 atmospheres absolute multiplies the plasma-dissolved fraction several-fold ESTABLISHED, 35, 36, 37.

1.2 The bottleneck is the last fifty micrometres

The rate-limiting step for tissue oxygenation is not lung-to-blood transfer but capillary-to-mitochondrion transfer. Poole, Musch, and Colburn describe this final passage as occurring over distances under 50 µm in skeletal muscle, across a sequence of barriers: dissociation from haemoglobin, transit across the red cell membrane, the endothelial surface layer, the endothelial cell, the interstitial space, the sarcolemma, cytoplasm, and finally the mitochondrial membranes ESTABLISHED, 40. Each interface contributes resistance. Their review explicitly challenges the simple Krogh-Erlang picture of a smooth pressure decrement from capillary to cell, and emphasises that diffusive conductance, not merely bulk blood flow, sets the ceiling.

1.3 Mitochondria tolerate remarkably low oxygen tension — until they do not

Using combined ^{1}H and ^{31}P magnetic resonance spectroscopy in resting human tibialis anterior during ischaemia, Lanza and colleagues measured the critical intracellular partial pressure of oxygen — the tension below which mitochondrial ATP synthesis becomes oxygen-limited — at 0.35 ± 0.20 Torr ESTABLISHED, 41. Two implications follow. First, healthy resting muscle operates with a very large oxygen safety margin, so adding oxygen to already-adequate tissue should not be expected to increase ATP synthesis. Second, the same study observed a 4.5-fold range of critical PO_2 across individuals, which is a caution against assuming uniform dose-response.

Where oxygen availability genuinely fails, the consequences are severe. In septic patients, skeletal muscle ATP concentrations were significantly lower in non-survivors than survivors, with complex I activity inversely correlated with shock severity ESTABLISHED, 42. Oxidative phosphorylation accounts for the large majority of whole-body oxygen consumption, so bioenergetic failure and oxygen delivery failure are tightly coupled.

1.4 Why injured and inflamed tissue is the interesting case

Oedema increases diffusion distance. Compression, microvascular thrombosis, and inflammatory infiltrate reduce effective perfusion. In these settings, arterial oxygen content is normal while local tissue oxygen tension is not. Transcutaneous oxygen tension measurement — a clinical standard for assessing limb perfusion — illustrates how low baseline skin oxygen tension is even in health: a validated electron paramagnetic resonance method reported 7.8 ± 0.8 to 22.0 ± 1.0 mmHg on the volar forearm and 8.1 ± 0.3 to 23.4 ± 1.3 mmHg on the foot in ten healthy subjects ESTABLISHED, 29.

INFERENCE If a delivery route existed that raised oxygen tension in superficial and subcutaneous tissue without depending on the compromised local circulation, it would address the specific bottleneck that pulmonary oxygen supplementation does not. This is the mechanistic case for transdermal delivery. It is a case for the *rationale*, not for the *result*.

2. Nanobubble Physics

2.1 Definitions

An **ultrafine bubble** or **bulk nanobubble** is a gas-filled cavity suspended in bulk liquid with a diameter below 1 µm; most working definitions and most measured preparations centre well below 200 nm ESTABLISHED, 1, 6. These are distinct from **surface nanobubbles**, which are gaseous domains adhering to a solid-liquid interface and which have been imaged by atomic force microscopy ESTABLISHED, 3. Sayadi and colleagues, reviewing the wound-care literature, define the practical micro/nanobubble range as 100 µm down to under 1 µm, and note stability "for hours" ESTABLISHED, 12.

2.2 The Laplace pressure paradox

The Young-Laplace equation gives the excess internal pressure of a spherical bubble as $\Delta P = 2\gamma/r$, where γ is surface tension (approximately 0.072 N/m for clean water at 25 °C) and r is bubble radius. The consequences at small radii are extreme.

The following values are calculated directly from the Young-Laplace and Stokes equations using standard constants for water at 25 °C. They are arithmetic, not citations, and readers can reproduce them.

Property	Macrobubble (1 mm)	Microbubble (50 µm)	Nanobubble (100 nm)	Claimed Bimini scale (10 nm)
Diameter	1,000 µm	50 µm	0.1 µm	0.01 µm
Laplace excess pressure ($2\gamma/r$)	~0.29 kPa (~0.003 atm)	~5.8 kPa (~0.06 atm)	~2.9 MPa (~28 atm)	~29 MPa (~285 atm)
Stokes rise velocity (order of magnitude)	~0.2–0.5 m/s (Stokes overestimates; inertial regime)	~1.4 mm/s (~5 m/h)	~5 nm/s (~0.5 mm/day)	~0.05 nm/s (negligible)
Dominant transport mode	Buoyant rise	Buoyant rise	Brownian motion	Brownian motion
Surface area to volume ($3/r$)	6×10^{3} m^{-1}	1.2×10^{5} m^{-1}	6×10^{7} m^{-1}	6×10^{8} m^{-1}
Observed persistence	Seconds	Seconds to minutes	Days to months, reported **[1, 2]**	Not independently verified at this size

The paradox is immediate. At 100 nm diameter, the internal gas pressure is roughly 28 atmospheres. Classical Epstein-Plesset diffusion theory predicts such a bubble should dissolve into the surrounding undersaturated liquid within microseconds to milliseconds. It does not. Seddon and Lohse quantified this

discrepancy for surface nanobubbles as 10–11 orders of magnitude longer survival than classical expectation ESTABLISHED, 3.

2.3 Proposed stabilisation mechanisms

No single mechanism has consensus. The 2025 review by Chen, Gao, and Zhang catalogues the current candidate models and states plainly that bulk nanobubble stability "cannot be depicted by the current theories" from either thermodynamic or dynamic perspectives ESTABLISHED, 1. Candidates include interfacial charge, a compressed contaminant monolayer at the gas-liquid interface, and interfacial thermal fluctuations.

The electrostatic model has the most direct empirical support. Arias-Sanchez and colleagues generated nanobubbles by shear using oxygen, nitrogen, air, and argon, and measured zeta potentials between −30 and −60 mV — a magnitude consistent with colloidal stabilisation by electrostatic repulsion under DLVO theory ESTABLISHED, 2. They produced approximately 100 nm bubbles at ultrahigh number concentrations using a low-energy (~125 Wh) generator. Notably for oxygen specifically, their argon and nitrogen preparations resisted physical perturbation better than air and oxygen preparations, which they attributed to oxygen's reactivity and polarisability. This is a relevant caution: oxygen nanobubbles may be *less* stable than the general nanobubble literature implies.

Supporting evidence comes from the destabilisation side. Tanaka and colleagues reduced ultrafine bubble number concentration by 90% using 30 minutes of indirect ultrasonic irradiation, and traced the mechanism to a reduction in the magnitude of zeta potential driven by pH and conductivity changes ESTABLISHED, 6. If reducing surface charge destroys the bubbles, surface charge is plausibly what sustains them.

Molecular dynamics work adds nuance. Mi, Zhang, and Ge showed that nanobubble stable states shift between stretched and compressed regimes depending on gas density, system scale, and temperature, and that Laplace pressure falls and interfaces become more deformable under compression ESTABLISHED, 5. A parallel simulation study by Zhou and colleagues found that the Einstein-Stokes relation — the basis for sizing nanobubbles by dynamic light scattering or nanoparticle tracking analysis — deviates substantially for bubbles above roughly 3 nm radius, because bubble deformability produces a cushioning effect during collisions ESTABLISHED, 8.

Mørch's review of cavitation nuclei frames the same physics from the fluid-mechanics side, describing stabilised gaseous voids with an interfacial "skin" permitting diffusive balance with dissolved gas ESTABLISHED, 4.

2.4 Generation and measurement

Reported generation routes include shear/hydrodynamic cavitation, pressurised dissolution, swirling liquid flow, acoustic cavitation, and membrane and microfluidic methods ESTABLISHED, 2, 6, 7, 9. Bu and Alheshibri's review of ultrasonic generation concludes that the generation and stability mechanisms in the acoustic field

remain unclear ESTABLISHED, 7. Paknahad and colleagues note that current state-of-the-art methods are not designed to produce simultaneously high concentration and low polydispersity, and propose microfluidics as a route to both ESTABLISHED, 9.

Measurement is contested. Arias-Sanchez found nanoparticle tracking analysis more accurate than dynamic light scattering for nanobubble characterisation ESTABLISHED, 2. Both techniques infer size from Brownian diffusion via Einstein-Stokes, whose applicability to deformable gas cavities is exactly what Zhou and colleagues call into question ESTABLISHED, 8.

2.5 A direct note on Bimini's stated bubble size

Bimini states its nanobubbles measure 0.005–0.02 microns (5–20 nm), averaging 0.01 micron, at more than 200 million bubbles per millilitre, and describes them as up to 5,000 times smaller than a human skin pore COMPANY REPORTED.

A skeptical reader should note the following. Published, peer-reviewed bulk nanobubble preparations cluster near 100 nm, an order of magnitude larger ESTABLISHED, 2. At 10 nm diameter, calculated Laplace pressure exceeds 280 atmospheres, and no published stabilisation model has been demonstrated to hold at that scale. Furthermore, nanoparticle tracking analysis has a practical lower detection limit that is well above 10 nm for low-refractive-index objects such as gas bubbles, which raises the question of what instrument produced the figure and under what conditions. This document does not assert that Bimini's figure is wrong. It asserts that the figure is not corroborated by the peer-reviewed nanobubble literature, and that a purchaser conducting diligence is entitled to ask for the sizing methodology, the instrument, the sample preparation, and the raw distribution.

2.6 The dissolved oxygen figure is separable from the nanobubble claim

Bimini states its systems maintain approximately 28 ppm dissolved oxygen using 95%+ pure oxygen, against roughly 8 ppm in ordinary tap water COMPANY REPORTED.

The following is first-principles arithmetic using standard oxygen solubility values, not a citation. Air-equilibrated water at 25 °C holds roughly 8.3 mg/L of dissolved oxygen, and the oxygen fraction of air is about 20.9%. Under Henry's law, equilibrating the same water with a 95% oxygen gas phase at one atmosphere would scale this to approximately 38 mg/L at 25 °C, and roughly 30–32 mg/L at typical bath temperatures near 35 °C. A measured value of 28 ppm therefore sits slightly *below* pure-oxygen equilibrium saturation at bath temperature.

This is an important and honest point. The 28 ppm figure is fully explained by Henry's law equilibration with a high-purity oxygen gas stream. It does not, by itself, require or demonstrate the existence of nanobubbles. The distinct contribution nanobubbles would make is (a) persistence of the elevated concentration against off-gassing during a 30–60 minute session, and (b) the possibility of a gas reservoir in excess of dissolved saturation. Both are plausible INFERENCE and both are measurable. Neither has been published for this device.

3. The Skin as a Gas Exchange Surface

This is the section on which the technology is most vulnerable, and it deserves the most rigour.

3.1 What is genuinely established

Human skin takes up atmospheric oxygen. This is not marketing; it has been known since the nineteenth century and was quantified with modern instrumentation by Stücker and colleagues in *The Journal of Physiology* in 2002 ESTABLISHED, 24. Using an oxygen fluxoptode on the volar forearm of 20 volunteers across age groups, they measured transcutaneous oxygen flux at 0.53 ± 0.27 mL $O_2 \cdot min^{-1} \cdot m^{-2}$ at a normal skin surface oxygen partial pressure of 163 ± 9 Torr. Five minutes of suprasystolic arterial occlusion increased that flux by only 9.5 ± 6.3%, indicating that the flux is driven overwhelmingly by the external gradient rather than by blood supply.

Their central conclusion is the one that matters here: combining their measurements with published skin oxygen diffusion properties and simulated intracutaneous oxygen profiles, **the upper skin layers to a depth of 0.25–0.40 mm are almost exclusively supplied by external oxygen**, with blood-borne oxygen transport having only a minor influence at that depth.

3.2 What this does and does not license

It licenses the statement that skin is a real, quantifiable gas exchange surface, and that raising the external oxygen partial pressure at the skin surface will raise oxygen tension in the outer few hundred micrometres.

It does not license the statement that oxygen delivered at the skin surface reaches muscle. Stücker's own framing is that the *upper* skin is externally supplied and that deeper tissue is not. The dermis extends to 1–2 mm; subcutaneous fat and muscle lie beyond that. The measured flux — approximately 0.5 mL O_2 per minute per square metre — is small in absolute terms. For scale, a resting adult consumes roughly 250 mL of oxygen per minute across a body surface area near 1.8 m^2, so cutaneous uptake represents well under 1% of total oxygen consumption. Bimini's own FAQ concedes this, estimating skin uptake at 1–2% of total oxygen under normal conditions COMPANY REPORTED, which is broadly consistent with the physiology.

3.3 The molecular size argument, examined carefully

Bimini's materials invoke the 500 Dalton rule and note that molecular oxygen is 32 Daltons COMPANY REPORTED. The rule is real: Bos and Meinardi argued in *Experimental Dermatology* that a compound's molecular weight must be below 500 Da to permit skin absorption, supported by the observation that essentially all common contact allergens, topical dermatological agents, and transdermal patch drugs fall below that threshold ESTABLISHED, 25.

Two qualifications are essential and are frequently omitted.

First, the 500 Dalton rule is a *necessary but not sufficient* condition. It states an upper bound above which penetration does not occur; it does not state that everything below 500 Da penetrates freely or in therapeutically meaningful quantity. Flux through the stratum corneum also depends on lipophilicity, partition coefficient, concentration gradient, and vehicle.

Second — and this is the critical logical point — the rule applies to **dissolved molecules**, not to particles. A 10 nm gas bubble is not a 32 Dalton molecule. It is a colloidal object roughly the size of a small protein complex. If oxygen crosses the stratum corneum from nanobubble water, the most parsimonious mechanism is that it crosses **as dissolved molecular oxygen**, driven by the elevated dissolved-oxygen gradient the nanobubbles help sustain, not as an intact bubble threading through a pore INFERENCE. The nanobubbles would then function as a reservoir maintaining the gradient, which is a coherent and defensible mechanism — and a more modest one than "bubbles pass through pores."

3.4 The nanoparticle penetration literature does not say what it is often said to say

Bimini's blog states that peer-reviewed studies confirm particles below 0.1 microns readily cross the stratum corneum via intercellular lipid pathways and follicular routes COMPANY REPORTED. The actual literature is considerably more equivocal.

Lauterbach and Müller-Goymann, reviewing lipid nanoparticles for dermal and transdermal delivery, state that penetration and permeation into and across deeper skin layers are **restricted** by the stratum corneum barrier, and that the hair follicle is the route offering genuine potential — with an appropriate size specification of up to approximately 640 nm for follicular penetration ESTABLISHED, 27. Bellefroid and colleagues similarly describe the stratum corneum as the first barrier that must be overcome, with multiple additional intracellular barriers thereafter ESTABLISHED, 28.

Most directly, Saweres-Argüelles and colleagues reviewed skin absorption of inorganic nanoparticles across in vivo and in vitro models and concluded that nanoparticles **rarely reach the blood circulatory system** through intact skin ESTABLISHED, 26.

Bimini's own framing on the "how it works" page invokes skin *pores* at 50 µm as the aperture COMPANY REPORTED. Pores in the dermatological sense are follicular and sweat duct openings; they are not the primary transdermal route for gases, and the intercellular lipid pathway of the stratum corneum — the actual route for small molecules — has effective aqueous pore dimensions on the order of a few nanometres, not micrometres. The "5,000 times smaller than a pore" framing is therefore not the relevant comparison.

3.5 What immersion adds, and it is not trivial

There is a real and underused argument here. Warm water immersion produces substantial cutaneous vasodilation. Brunt and colleagues demonstrated that eight weeks of hot water immersion improved cutaneous microvascular function via enhanced nitric-oxide-dependent dilation, with local heating plateau rising from 42 ± 6% to 53 ± 6% of maximal cutaneous vascular conductance ESTABLISHED, 50. Green and colleagues showed that repeated forearm immersion in 42 °C water improves microvascular vasodilator function, and that the effect is abolished when shear stress is blocked by cuff inflation — establishing hyperaemia and shear as the obligatory stimulus ESTABLISHED, 51. McGarr and colleagues quantified cutaneous vasodilation during whole-body warm water immersion with core temperature clamped at 38.5 °C ESTABLISHED, 52.

INFERENCE Cutaneous vasodilation shortens the effective diffusion path between the skin surface and the capillary bed, and increases the perfused surface available to take up oxygen that has crossed the epidermis. Warm oxygenated water immersion therefore combines an elevated external gradient with a heat-induced increase in cutaneous perfusion. This is a genuinely more favourable configuration than either dry topical oxygen or cool immersion. It has not been directly tested.

Immersion also imposes hydrostatic loading with its own systemic effects — central blood volume translocation, increased stroke volume, altered regional perfusion — comprehensively reviewed by Pendergast and colleagues ESTABLISHED, 54. Any observed physiological change during immersion has multiple candidate causes.

3.6 Summary of the honest position on skin

Established: skin takes up external oxygen; the outer 0.25–0.40 mm is externally supplied; molecules under 500 Da can cross; warm immersion vasodilates skin.

Not established: that oxygen delivered at the skin surface reaches skeletal muscle in physiologically meaningful quantity; that intact nanobubbles traverse the stratum corneum; that oxygen nanobubble immersion raises deep tissue oxygen tension in humans.

4. Comparative Oxygen Delivery Modalities

The table below is deliberately fair to hyperbaric oxygen therapy, which has by a wide margin the deepest evidence base of any modality discussed.

	HBOT	Topical / normobaric O_2 (wound)	Exercise with oxygen (EWOT) / normobaric hyperoxia	Oxygen nanobubble immersion
Pressure	1.5–3.0 ATA, typically 2.0–2.5 **[35, 37]**	1 ATA	1 ATA	1 ATA
Primary mechanism	Massive increase in plasma-dissolved O_2; downstream reactive oxygen and nitrogen species signalling **[35, 36]**	Direct diffusion into exposed wound bed	Elevated inspired FiO_2 raising arterial and tissue oxygenation **[49]**	Elevated dissolved O_2 at skin surface plus heat-induced cutaneous vasodilation INFERENCE
Dissolved O_2 achieved	Plasma-dissolved fraction increased approximately 5- to 20-fold **[36]**	Locally high at wound surface; not systemic	Modest systemic increase; quadriceps tissue oxygenation index measurably higher at FiO_2 40% vs 21% **[49]**	~28 ppm in bath water COMPANY REPORTED; delivered tissue dose unmeasured
Route	Pulmonary	Direct wound contact	Pulmonary	Transdermal (proposed)
Typical session	60–90 min, supervised, clinical	Continuous or intermittent, days to weeks	15–40 min with exercise	30–60 min immersion COMPANY REPORTED
Indicative cost	US$150–400 per clinic session; chambers US$15,000–150,000+ COMPANY REPORTED MARKET FIGURES	Device and consumable dependent	Concentrator plus mask, low four figures	NanoJet Eco US$10,895; NanoJet Pro US$24,995 COMPANY REPORTED
Risk profile	Barotrauma, middle ear, CNS and pulmonary oxygen toxicity, confinement anxiety; oxygen toxicity mechanisms well characterised **[39]**	Low; local	Low at moderate FiO_2 and duration	Low; risks are those of warm immersion generally. No published adverse event data for this device.
Evidence maturity	Highest. RCTs and systematic reviews support refractory diabetic wounds and radiation injury; strong basis for CO poisoning **[35, 37]**	Moderate. Multiple meta-analyses, pooled RR ~1.6–1.8, but persistent risk-of-bias concerns **[30, 31, 32, 33]**	Mixed. Tissue oxygenation increases are measurable; performance benefit inconsistent **[49, 58]**	Lowest. Preclinical nanobubble literature only; no indexed human immersion trial

Notes of fairness

HBOT's evidence base is real and should not be diminished. Thom's review documents systematic-review and randomised-trial support for refractory diabetic wound healing and radiation injury, with mechanisms grounded in reactive species signalling rather than oxygen delivery alone ESTABLISHED, 35. Sethuraman and Thom argue for HBOT in acute carbon monoxide poisoning at 2.5–3.0 ATA on the strength of both preclinical work and prospective randomised trials ESTABLISHED, 37. HBOT's mitochondrial effects are dose- and duration-dependent, with short-course exposure capable of deleterious effects on mitochondrial activity and reactive oxygen species production and longer courses improving both ESTABLISHED, 36.

Equally, HBOT is not a general recovery tool. Two randomised, blinded trials found hyperbaric oxygen ineffective for delayed-onset muscle soreness and exercise-induced muscle injury, using isometric strength, soreness rating, limb circumference, creatine kinase, malondialdehyde, and magnetic resonance imaging as endpoints ESTABLISHED, 55, 56. Barnett's review of between-session recovery modalities in elite athletes concluded there was no substantial scientific evidence supporting any of the modalities reviewed, hyperbaric oxygen included ESTABLISHED, 57. This matters for the present document: it establishes that "delivers more oxygen" does not automatically translate to "accelerates recovery," and any modality claiming otherwise carries the burden of proof.

Bimini's own comparison page is, to its credit, explicit that HBOT is the correct choice for its approved indications, listing decompression sickness, non-healing diabetic and radiation wounds, carbon monoxide poisoning, gas gangrene, severe anaemia, crush injury, and compromised grafts, and directing readers to consult a physician COMPANY REPORTED. That is the appropriate posture for a wellness device.

5. Downstream Physiology

Everything in this section is **mechanism**, not **outcome**. It describes what elevated tissue oxygen tension does when it occurs. It does not establish that nanobubble immersion produces elevated tissue oxygen tension.

5.1 Mitochondrial ATP synthesis

Oxidative phosphorylation is the terminal oxygen sink and accounts for the large majority of cellular oxygen consumption ESTABLISHED, 42. Below the critical intracellular PO_2 of approximately 0.35 Torr, ATP synthesis becomes oxygen-limited ESTABLISHED, 41. Above it, oxygen is not rate-limiting, and adding more does not increase ATP output. This is the single most important constraint on mechanistic claims in this field: **in adequately oxygenated tissue, supplemental oxygen cannot increase ATP synthesis, because oxygen is not the limiting substrate** INFERENCE FROM 41.

The corollary is that any plausible benefit is confined to tissue that is genuinely hypoxic — injured, oedematous, inflamed, or poorly perfused. This narrows the plausible target population considerably and should temper claims made to healthy athletes.

5.2 HIF-1α signalling

Hypoxia-inducible factors are the master transcriptional regulators of the cellular oxygen response, driving angiogenesis, metabolic reprogramming, extracellular matrix remodelling, epithelial-mesenchymal transition, motility, and stem cell maintenance ESTABLISHED, 43. HIF-mediated metabolic adaptation shifts cells toward glycolysis and reshapes glucose, glutamine, and lipid handling ESTABLISHED, 44.

The naive inference — that raising tissue oxygen suppresses HIF and is therefore uniformly beneficial — is not safe. HIF signalling is adaptive as well as pathological. Furthermore, Kiers and colleagues demonstrated in both murine endotoxaemia and human experimental endotoxaemia that short-term hypoxia *dampens* the pro-inflammatory cytokine response, via enhanced adenosine release and adenosine 2B receptor stimulation, and showed explicitly that this effect was **independent** of HIFs ESTABLISHED, 45. Hypoxia and inflammation are intertwined, but the relationship is not a simple monotonic one in which more oxygen means less inflammation.

5.3 Collagen synthesis

Collagen maturation requires post-translational hydroxylation of proline and lysine residues by dioxygenases that use molecular oxygen as a co-substrate. This is standard biochemistry and is the mechanistic basis for the observation that hypoxic wounds heal poorly. Bimini's materials cite proline hydroxylase activation as a downstream effect of transdermal oxygen COMPANY REPORTED. The enzymology is sound; the demonstration that transdermal nanobubble delivery raises dermal oxygen sufficiently to alter collagen synthesis rate has not been published INFERENCE.

5.4 Oxidative stress is the counterweight

Oxygen is not benign at elevated tension. Allen, Demchenko, and Piantadosi review the cellular mechanisms of oxygen toxicity, focusing on the interaction of nitric oxide with reactive oxygen species and noting that the anatomical localisation of nitric oxide release — which itself depends on whether exposure is normobaric or hyperbaric — determines whether toxicity emerges and in what form ESTABLISHED, 39. Schottlender and colleagues show a biphasic pattern for hyperbaric oxygen: short-course exposure can be deleterious to mitochondrial activity and increase reactive oxygen species, while longer courses improve mitochondrial activity and reduce reactive oxygen species through upregulated antioxidant defences ESTABLISHED, 36.

INFERENCE Because nanobubble immersion is normobaric and delivers oxygen to a limited tissue depth, the systemic oxidative burden should be far below that of hyperbaric exposure. This is a reasonable expectation from the physics but is an untested assumption for this modality. It should not be presented as a demonstrated safety finding.

5.5 Satellite cell dynamics

Resistance exercise expands Pax7-positive satellite cells in human skeletal muscle by roughly 50% above pre-exercise levels at 24–72 hours, with a large pooled effect size, and this response persists into older age despite a smaller baseline stem cell reserve ESTABLISHED, 59. This defines the biological window in which any recovery intervention would need to act. It provides a rational basis for the 24–72 hour post-exercise timing of recovery protocols. It says nothing about oxygen.

6. Measured Outcomes

6.1 Bimini's own reported data

The following are stated on Bimini's public materials and are reported here verbatim as COMPANY REPORTED:

- A study conducted at Rice University tested the Bimini NanoJet on more than 100 collegiate athletes.
- Reported result: 43–46% improvement in performance and recovery metrics versus control conditions, including reduced delayed-onset muscle soreness indicators and faster return to force production.
- Reported result: muscle oxygen saturation measured by near-infrared spectroscopy rising from a resting baseline of approximately 50% to above 90%, beginning within 5–8 minutes of immersion and peaking at approximately 15–20 minutes, with elevation persisting 1–4 hours post-session.
- Reported timing of benefit: improvement observed 1–24 hours after treatment, most pronounced in the first few hours.
- Reported safety: zero oxygen toxicity observed at any level; zero adverse events across six months of clinical observation.
- Bimini describes the study as "peer-reviewed and published."
- Bimini additionally references clinical research in partnership with Methodist Hospital documenting improved healing timelines in soft tissue and skeletal injury rehabilitation, without stated numerical outcomes.
- Session protocol: 30–45 minutes for maintenance and recovery, 45–60 minutes for injury; water 78–100 °F; daily use described as safe.
- Water specification: approximately 28 ppm dissolved oxygen at 95%+ oxygen purity; more than 200 million nanobubbles per millilitre; bubble diameter 0.005–0.02 µm.

6.2 Independent retrieval status

Systematic PubMed searches conducted for this document, using multiple query formulations covering nanobubble plus athlete plus muscle oxygen saturation, and transdermal plus oxygen plus nanobubble plus immersion, returned **zero indexed records**. The Rice University study, the Methodist Hospital work, and the near-infrared spectroscopy dataset could not be located in PubMed. This does not mean the work was not performed. It does mean the work has not entered the indexed peer-reviewed literature and cannot presently be examined by a third party.

6.3 Methodological limitations a reviewer would raise

Stating these directly is not a concession. It is the only way this document earns credibility with the audience it is written for.

a) The near-infrared spectroscopy confound is the central issue. SmO_2 is not a measure of tissue oxygen partial pressure. It is a measure of the oxygenation state of haemoglobin and myoglobin within the volume of tissue the near-infrared light traverses. Barstow's methodological review — a *Cores of Reproducibility in Physiology* article — details the confounders explicitly, including adipose tissue thickness, skin blood flow, and scattering, and provides recommendations to reduce variability and error in collection and interpretation ESTABLISHED, 46.

The specific problem here is direct. Warm-water immersion causes marked cutaneous vasodilation ESTABLISHED, 50, 51, 52. Cutaneous vasodilation floods the superficial layers of the near-infrared light path with oxygenated haemoglobin. **A rise in measured SmO_2 during warm-water immersion is fully expected from vasodilation alone, with no transdermal oxygen transfer whatsoever.** Distinguishing the two requires a control condition: identical warm-water immersion, identical temperature and duration, with and without oxygen nanobubble infusion, with participants and operators blinded to condition. Without that control, a 50%-to-90% SmO_2 excursion is uninterpretable as evidence of oxygen delivery.

A secondary point: a resting baseline SmO_2 of approximately 50% is at the low end of typical values for a healthy athlete at rest, which invites questions about probe placement, device calibration, and adipose tissue thickness correction. Feldmann and colleagues established a validated protocol for verifying a device's 0–100% scale using arterial occlusion, testing repeatability, reproducibility, and face validity ESTABLISHED, 47. A published dataset should report whether such physiological calibration was performed.

b) Blinding. No blinding procedure is described. Recovery, soreness, and mental clarity outcomes are highly susceptible to expectation effects, particularly in athletes using a visibly novel and expensive device.

c) Sample and design. "More than 100 collegiate athletes" is a reasonable sample size, but no information is given on randomisation, control condition, allocation concealment, dropout, or pre-registration. A 43–46% improvement is a large effect; large effects in unblinded, uncontrolled recovery studies are common and frequently do not replicate.

d) Composite outcomes. "Performance and recovery metrics" is not a defined endpoint. Which metrics, measured how, at what timepoints, with what statistical correction for multiple comparisons?

e) Publication status. Bimini describes the study as peer-reviewed and published, yet it is not retrievable in PubMed. Purchasers should request the full citation, journal name, and DOI, and verify independently.

f) Conflict of interest. The study was conducted on a Bimini device with Bimini involvement. This does not invalidate it. It does mean it requires independent replication before being treated as established.

g) The safety framing needs care. Bimini cites literature holding that 100% oxygen can be tolerated for 24–48 hours without serious tissue damage COMPANY REPORTED. That statement concerns *inhaled* oxygen and pulmonary oxygen toxicity, and the underlying mechanisms are more nuanced than a single tolerance window suggests ESTABLISHED, 39. It is not directly applicable to transdermal exposure and does not constitute

safety evidence for this device. The more defensible safety argument is simply that warm-water immersion at 78–100 °F is a low-risk activity, that the modality is normobaric, and that no adverse events have been reported.

6.4 The adjacent published literature

What *is* published, and what it supports:

Nanobubble oxygen delivery to tissue (preclinical). Aoki and colleagues applied oxygen nanobubble water topically to full-thickness skin wounds in 36 Sprague-Dawley rats, including an ischaemic bi-pedicle flap model, and reported enhanced healing ESTABLISHED, 13. Sayadi and colleagues quantified wound healing with oxygenated micro/nanobubbles in a preclinical burn model, targeting burn wound conversion in the zone of stasis ESTABLISHED, 15. Banche and colleagues showed chitosan/perfluoropentane oxygen-loaded nanobubbles promoted wound healing processes in hypoxic human keratinocytes with acceptable biocompatibility ESTABLISHED, 14.

Oxygen nanobubble delivery vehicles. Han and colleagues, in *Nature Communications*, incorporated exosome-coated oxygen nanobubbles into a hydrogel and showed alleviation of wound hypoxia alongside improved intracellular cargo delivery ESTABLISHED, 16. Ren and colleagues demonstrated an oxygen nanobubble hydrogel retaining and releasing oxygen for up to 34 days ESTABLISHED, 17. Han and colleagues also built an enzymatic cascade nanobubble system for simultaneous hypoxia mitigation and reactive oxygen species scavenging ESTABLISHED, 18.

A negative and important result. Sanno and colleagues tested hydrogen, oxygen, and ozone nanobubbles on fibroblast migration and proliferation in scratch wound assays. Oxygen nanobubbles showed **no statistically significant difference from control** at either 24 or 48 hours; ozone nanobubbles were significantly cytotoxic at 48 hours ESTABLISHED, 20. This is a well-designed in vitro study finding no fibroblast effect from oxygen nanobubbles, and it is cited here deliberately.

Topical oxygen in humans. Three meta-analyses converge on a modest positive effect with quality caveats. Putri and colleagues pooled seven RCTs and two controlled observational studies, finding healed wound rates of 43.3% with topical oxygen versus 25.8% control (RR 1.77, 95% CI 1.18–2.64, p = 0.005) ESTABLISHED, 30. Carter and colleagues pooled four RCTs in Wagner grade 1–2 diabetic foot ulcers, finding RR 1.59 (95% CI 1.07–2.37, p = 0.021), with overall GRADE-rated evidence quality of moderate and risk-of-bias judgements of one low-risk and three some-risk trials ESTABLISHED, 31. Sun and colleagues pooled seven RCTs across 614 participants, finding a healing rate RR of 1.63 (95% CI 1.33–2.00) with no increase in adverse events ESTABLISHED, 32. Nagarsheth and colleagues, reviewing 22 articles, found significant effects on complete healing but no significant effect on percent wound area reduction, ulcer grade, or pain scores, and stated that most included studies had high risk of bias due to lack of blinding, single-arm design, or case-report format ESTABLISHED, 33.

Nanobubbles as a dissolved-oxygen technology. The agricultural literature independently confirms that nanobubble generation raises and sustains dissolved oxygen in water at scale. Zhou and colleagues ran a two-year field trial of micro/nanobubble oxygation in spring maize at dissolved oxygen concentrations of 10, 20, and 30 mg/L, reporting increased root dry weight, yield, and quality ESTABLISHED, 22. Minamikawa and Makino showed that irrigation with bulk oxygen nanobubble water oxidised flooded paddy soil, following an earlier finding of 21% seasonal methane emission reduction ESTABLISHED, 21. Li and colleagues examined micro/nanobubble effects on drip emitter clogging and noted the significant dissolved-oxygen increase ESTABLISHED, 23. These are not medical studies, but they are independent, peer-reviewed confirmation that the core water-chemistry claim is real.

Where the field stands overall. Sayadi and colleagues' 2018 review of topical oxygen therapy and micro/nanobubbles concluded that the efficacies of existing tissue oxygen delivery systems, including HBOT and topical oxygen therapy, "have yet to be fully substantiated," and positioned micro/nanobubbles as a new and unproven modality ESTABLISHED, 12. Afshari and colleagues reviewed nanobubble oxygenation for hypoxic patients and described a range of proposed physiological and pharmacological effects ESTABLISHED, 19. Neither review reports a human transdermal immersion trial.

7. Open Questions and Research Roadmap

The following are genuinely unknown. A purchaser or clinical partner asking these questions is asking the right ones.

1. Does oxygen nanobubble immersion raise tissue oxygen tension through intact human skin, and to what depth? This is the foundational question and it is answerable. The instrument exists: transcutaneous oximetry, ideally the electron paramagnetic resonance method validated by Kmiec and colleagues, which measures only oxygen diffusing through the skin surface and is not itself oxygen-consuming ESTABLISHED, 29. Required design: within-subject crossover, identical warm-water immersion with and without oxygen infusion, participants and assessors blinded, $tcpO_2$ at multiple sites, with depth resolution if possible.

2. Is the effect distinguishable from warm-water vasodilation? Directly follows from question 1. This is the single most important control and its absence is the principal weakness of the current evidence base.

3. What is the actual bubble size distribution, measured how? Independent nanoparticle tracking analysis of NanoJet-generated water with reported instrument, dilution protocol, and full distribution — not a modal value. Given the known Einstein-Stokes deviations for deformable gas cavities ESTABLISHED, 8 and the argument between nanoparticle tracking analysis and dynamic light scattering ESTABLISHED, 2, orthogonal methods should be used.

4. How long do oxygen nanobubbles persist under bath conditions? Published stability work is largely at room temperature in still, clean water. A bath is 30–38 °C, agitated, contaminated with skin lipids, sweat, and surfactants, and open to atmosphere. Oxygen nanobubbles specifically were found more susceptible to physical perturbation than argon or nitrogen ESTABLISHED, 2. Decay kinetics under realistic use conditions are unknown.

5. Dose-response. No dose-response curve exists across dissolved oxygen concentration, bubble number density, water temperature, immersion duration, or session frequency. Bimini's protocols (30–60 minutes, 78–100 °F, daily to 3–4× weekly) appear to be empirically derived rather than dose-optimised COMPANY REPORTED.

6. Durability. Bimini reports elevation persisting 1–4 hours post-session COMPANY REPORTED. Whether any change outlasts the session, and whether repeated exposure produces adaptation as repeated heat exposure demonstrably does ESTABLISHED, 50, 51, 53, is unknown.

7. Population differences. Lanza and colleagues found a 4.5-fold range in critical PO_2 across individuals ESTABLISHED, 41. Adipose tissue thickness alters near-infrared spectroscopy signal substantially ESTABLISHED, 46. Age modifies cutaneous vasodilatory capacity ESTABLISHED, 52. Effects, if present, are unlikely to be uniform.

8. Does the heat component account for most of the benefit? Passive heat therapy alone reduces sympathetic activity, lowers blood pressure and C-reactive protein, reduces arterial wall thickness, and improves flow-mediated dilation ESTABLISHED, 53. A thermoneutral-water control arm would separate oxygen effect from heat effect. This is arguably the second most important missing control.

9. Are recovery outcomes real? Given that two blinded randomised trials found hyperbaric oxygen — a far more aggressive oxygen intervention — ineffective for exercise-induced muscle damage ESTABLISHED, 55, 56, the prior probability that a normobaric transdermal intervention improves recovery markers by 43–46% should be treated as low until independently replicated.

Proposed study sequence

- **Phase 0 (physics):** Independent characterisation of bubble size distribution, concentration, zeta potential, and decay kinetics under realistic bath conditions.
- **Phase 1 (delivery):** Blinded crossover $tcpO_2$ study, oxygenated versus non-oxygenated warm water, n ≈ 20–30, healthy adults. This is the study that decides whether the mechanism is real.
- **Phase 2 (dose):** If Phase 1 is positive, dose-response across dissolved oxygen concentration and duration.
- **Phase 3 (outcome):** Randomised, blinded, three-arm trial — oxygenated warm water, non-oxygenated warm water, passive rest — with pre-registered primary endpoints in an exercise-induced muscle damage model.

8. Practical Implications

What the evidence currently justifies

For athletes. The evidence justifies treating oxygen nanobubble immersion as a warm-water recovery modality with a plausible but unproven additional mechanism. Warm-water immersion itself has documented vascular effects ESTABLISHED, 50, 51, 53 and is a comfortable, low-risk, well-tolerated recovery practice. Athletes who find it valuable should feel free to use it on that basis. They should not expect it to substitute for sleep, nutrition, or load management, and they should treat reported percentage improvements in recovery as unverified.

For clinicians and physical therapists. The evidence does not justify substituting nanobubble immersion for hyperbaric oxygen therapy in any of HBOT's approved indications, nor for topical oxygen therapy in chronic wound care where the human trial evidence — though imperfect — actually exists ESTABLISHED, 30, 31, 32. It does not justify any therapeutic claim. It may reasonably be offered as an adjunct wellness modality alongside standard care, with the evidentiary limitations disclosed to the patient.

For athletic trainers. Warm-water immersion is compatible with, and may be preferable to, cold immersion for athletes in strength-adaptation phases, on the general principle that repeated post-exercise cold exposure has been argued to blunt some training adaptations. This is a reason to consider warm modalities generally; it is not specific to oxygen.

For facility owners. The commercial case is largely a service-differentiation and utilisation case, not an efficacy case. A NanoJet Pro at US$24,995 or Eco at US$10,895 COMPANY REPORTED competes on capital cost, session throughput, comfort, absence of supervision requirement, and absence of barotrauma and claustrophobia risk relative to hyperbaric alternatives — all of which are genuine, verifiable operational advantages independent of any physiological claim. Facilities should ensure marketing language stays within wellness bounds and does not make treatment claims, which carries regulatory exposure the device's classification does not support.

What the evidence does not justify

- Any claim that the device treats, heals, cures, or prevents injury, disease, or any medical condition.
- Any claim of equivalence to hyperbaric oxygen therapy. The mechanisms differ, the delivered oxygen dose differs by orders of magnitude, and the evidence bases are not comparable.
- Presenting the Rice University figures as peer-reviewed evidence until the citation is produced and independently verified.
- Presenting a rise in near-infrared spectroscopy SmO_2 during warm immersion as proof of transdermal oxygen delivery, absent a non-oxygenated warm-water control.

- Extrapolating in vitro or rodent wound-model nanobubble results to intact human skin. The stratum corneum is precisely the barrier those models bypass.

The reasonable summary

Oxygen nanobubble immersion is a physically coherent idea built on a genuine and well-characterised phenomenon — ultrafine bubble persistence — combined with a genuine and well-documented physiology — cutaneous oxygen uptake and heat-induced cutaneous vasodilation. The gap is between the mechanism and the demonstration. That gap is not unusually large, and it is closable with two or three well-designed studies. Until those studies exist, the appropriate register is confidence in the rationale and reserve about the outcome.

Appendix A: Full Reference List

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Citation source: PubMed (National Library of Medicine). All PMIDs and DOIs verified against PubMed records at the time of writing.

Appendix B: Glossary

ATA (atmospheres absolute) — Unit of absolute pressure. Sea level is 1 ATA. Clinical hyperbaric protocols typically run 2.0–3.0 ATA.

Bulk nanobubble — A gas cavity below 1 µm in diameter suspended freely in liquid, as distinct from a surface nanobubble adhering to a solid interface.

Corneocyte — The flattened, anucleate, keratin-filled cell that forms the stratum corneum. Intercellular lipid lamellae between corneocytes constitute the primary route for small-molecule permeation.

Critical PO_2 — The intracellular oxygen partial pressure below which mitochondrial ATP synthesis becomes limited by oxygen availability. Measured at approximately 0.35 Torr in resting human skeletal muscle.

Cutaneous vascular conductance (CVC) — Skin blood flow normalised to perfusion pressure, typically expressed as a percentage of maximal vasodilation. A standard index in thermal physiology.

DLVO theory — Derjaguin-Landau-Verwey-Overbeek theory, describing colloidal stability as the balance of van der Waals attraction and electrostatic double-layer repulsion. Invoked to explain nanobubble persistence.

Dynamic light scattering (DLS) — Particle sizing technique inferring hydrodynamic diameter from fluctuations in scattered light caused by Brownian motion.

Epstein-Plesset equation — Classical description of the dissolution of a gas bubble into surrounding liquid. Predicts sub-millisecond lifetimes for nanoscale bubbles, contradicting observation.

EWOT (exercise with oxygen therapy) — Exercise performed while breathing an elevated inspired oxygen fraction at normobaric pressure.

Henry's law — The principle that the concentration of a dissolved gas in a liquid is proportional to the partial pressure of that gas above the liquid. The basis for both hyperbaric plasma oxygen loading and bath dissolved-oxygen concentration.

HIF-1α (hypoxia-inducible factor 1 alpha) — Oxygen-sensitive transcription factor subunit; the master regulator of the cellular hypoxic response, driving angiogenesis, glycolytic shift, and matrix remodelling.

Hydrostatic pressure (immersion) — The pressure exerted by water on an immersed body, which translocates blood centrally and alters cardiac and renal function.

Krogh cylinder — Classical model treating each capillary as supplying oxygen to a surrounding cylinder of tissue. A useful first approximation, now recognised as an oversimplification.

Laplace pressure — The excess internal pressure of a curved gas-liquid interface, given by $2\gamma/r$. Scales inversely with radius and becomes extreme at nanoscale.

Micro/nanobubble (MNB) — Umbrella term in the wound-care literature for bubbles spanning roughly 100 µm down to below 1 µm.

Nanoparticle tracking analysis (NTA) — Particle sizing technique tracking individual scattering centres and inferring diameter from their Brownian displacement via the Einstein-Stokes relation.

Normobaric — At ambient atmospheric pressure, as opposed to hyperbaric.

Prolyl hydroxylase — Dioxygenase enzyme requiring molecular oxygen as a co-substrate; hydroxylates proline residues in both procollagen (enabling collagen triple-helix stability) and HIF-α (targeting it for degradation).

Reactive oxygen species (ROS) — Oxygen-derived radicals and non-radical oxidants. Both signalling intermediates and mediators of oxidative injury; central to hyperbaric oxygen's mechanism and its toxicity.

SmO_2 (muscle oxygen saturation) — Near-infrared spectroscopy-derived percentage saturation of haemoglobin and myoglobin within the interrogated tissue volume. Not equivalent to tissue oxygen partial pressure.

Stratum corneum — The outermost 10–20 µm layer of the epidermis; the principal physicochemical barrier to percutaneous absorption.

Stokes' law — Relates the terminal velocity of a small sphere in a viscous fluid to its radius squared. Predicts negligible buoyant rise for nanoscale bubbles.

Surface nanobubble — A nanoscale gaseous domain adhering to a solid-liquid interface, imaged by atomic force microscopy, with anomalously long lifetime.

$tcpO_2$ (transcutaneous oxygen tension) — Oxygen partial pressure measured at the skin surface, used clinically to assess limb perfusion and wound healing potential.

Topical oxygen therapy (TOT) — Delivery of supplemental oxygen directly to an open wound bed at normobaric pressure, as distinct from systemic hyperbaric administration.

Ultrafine bubble (UFB) — ISO-aligned term for a bubble with diameter below 1 µm. Synonymous in most usage with bulk nanobubble.

Zeta potential — The electrical potential at the slipping plane of a particle in suspension. Magnitudes above roughly 30 mV (positive or negative) indicate electrostatic colloidal stability. Measured at −30 to −60 mV for characterised nanobubble preparations.

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