| LOG ID | BOOK REFERENCE | RCT FILTER | CONFIDENCE TIER |
|---|---|---|---|
| **SEC 10.3** | CHAPTER 10: HARDENED INFRASTRUCTURE (Chaos Engineering) | **ON** | **CONSENSUS** |

AUDITED CLAIM

# VOLTAGE REGULATION (RETENTION)

SYSTEMS MODEL — AS STATED IN THE BOOK

> Clinically, repeated deliberate **breath retention (apnea)** increases physiological tolerance to **hypercapnia** (rising CO2), gradually desensitizing the autonomic nervous system's suffocation alarm.

VALIDATION QUERY

Does deliberate breath retention increase hypercapnia tolerance and reduce the autonomic panic response to air hunger?

EMPIRICAL FINDING

Clinical investigations into autonomic regulation demonstrate that repeated deliberate breath retention (apnea) increases physiological tolerance to hypercapnia (rising CO2 levels). By systematically exposing the body to rising CO2, individuals can gradually desensitize the autonomic nervous system's suffocation alarm, building tolerance and reducing panic-like reactivity to air hunger.

PRIMARY ANCHORS

→ Kyriakoulis et al., 2021, Frontiers in Psychiatry

→ Meuret et al., 2008, Journal of Psychiatric Research

ABOUT THIS RECORD

Each claim in the book is decompiled from its IT metaphor into a naked, falsifiable scientific claim, then anchored to a **primary peer-reviewed source**. Claim and anchor are queried against the Consensus academic database (200M+ papers) under a fixed protocol — top-tier **Q1/Q2 journals only**, preprints excluded, human studies only. If a hypothesis fails the audit, the build is rejected: the AI generates the syntax; the peer-reviewed grid validates the physics.

CONFIDENCE TIERS

- **CONSENSUS ◀ this log** — broadly established, highly replicated mechanics.
- **EMERGING** — plausible, actively researched; no universal consensus yet.
- **EXPERIMENTAL** — contested, extrapolated, or purely theoretical.

**RCT FILTER** — Controlled Studies is ON for interventions (a forced action must beat a control) and OFF for mechanisms (so foundational neuroscience isn't blocked).

# Yes, **deliberate breath retention** appears to **increase hypercapnia tolerance**, but **panic-response reduction** is less directly proven.

## 1. Introduction

Deliberate breath retention appears to increase physiological tolerance to hypercapnia, especially in trained divers and apnea-trained individuals, but evidence that it reliably reduces the autonomic panic response to air hunger is more limited and indirect. Trained breath-hold divers tolerate higher arterial CO2 and lower O2 during apnea than non-divers, and even short daily apnea training can lengthen breath-hold duration and strengthen the diving response (Kyriakoulis et al., 2021). Repeated apnea exposure is also associated with reduced behavioral and ventilatory sensitivity to CO2 in experienced divers (Kyriakoulis & Caballero, 2025).

The panic-related question is more contested. Panic disorder is consistently linked to heightened CO2 sensitivity and stronger suffocation-related responses during respiratory challenges (Rassovsky et al., 2006; McIntosh et al., 2020; Gorman et al., 1997). But direct studies of breath holding in panic disorder have produced mixed results: some found greater physiological reactivity or shorter apnea times in panic patients, while others found similar anxiety increases across panic, generalized anxiety, and control groups during repeated breath holds (Rassovsky et al., 2006; Roth et al., 1998; Zandbergen et al., 1992). Interventions that normalize CO2 handling rather than simply prolong breath holding, such as capnometry-assisted respiratory training, show clearer reductions in panic severity and anxiety sensitivity ( Meuret et al., 2008; Meuret et al., 2023).

**Does practicing deliberate breath retention increase physiological tolerance to hypercapnia and reduce the autonomic panic response associated with air hunger?** N = 5

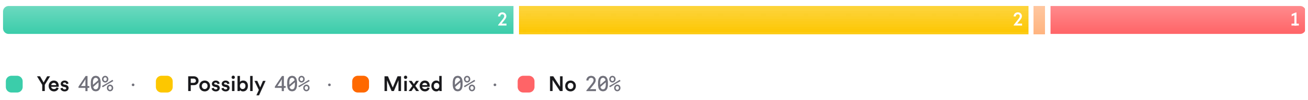


FIGURE 1 Consensus on breath retention, hypercapnia, and panic response

The literature supports a **yes** for hypercapnia tolerance in trained or repeatedly exposed people, but only a **qualified yes** for reducing panic-like autonomic responses. The second claim relies more on adjacent evidence from diving-response activation, CO2-targeted breathing therapy, and slow-breathing exposure than on direct long-term breath-retention trials (Kyriakoulis et al., 2021; Meuret et al., 2008; Szulczewski, 2019).

## 2. Methods

The search ran across more than 170 million research papers indexed by Consensus, including Semantic Scholar, PubMed, and related sources. The workflow identified 70 papers in the initial targeted search, expanded through citation crawling and parallel query reformulations, screened 240 records with machine-learned relevance filtering, and retained 150 eligible papers after thresholding and deduplication. The 50 most relevant human, controlled-study papers were included for synthesis here.

### Search Strategy

**1.1M** Retrieved → **1.9K** Eligible → **50** Included

22 searches

1 citation graph use

All papers retrieved from 22 searches and 1 citation graph use.

Papers meeting relevance and quality criteria, after deduplication

Top papers selected to be included in the final analysis

FIGURE 2 Deep search screening and inclusion flow

Searches combined direct apnea terms with adjacent concepts including $CO_2$ sensitivity, diving response, panic disorder, slow breathing, and capnometry-guided retraining.

## 3. Results

### 3.1 Key Papers

Three papers anchor this corpus because they address the question from complementary angles: trained-apnea physiology, panic-related autonomic effects, and $CO_2$-targeted clinical intervention. The diving-response review synthesizes the strongest direct evidence for apnea-related $CO_2$ tolerance (Kyriakoulis et al., 2021), the panic/CFI study tests autonomic and symptom effects in clinical and control groups (Kyriakoulis et al., 2021), and capnometry-assisted therapy shows that changing $CO_2$ regulation can improve panic outcomes ( Meuret et al., 2008).

| Paper | Summary |
|---|---|
| (Kyriakoulis & Caballero, 2025) | Trained divers show **higher $CO_2$ tolerance** (Kyriakoulis et al., 2021) |
| (Chiron et al., 2025) | Raising **end-tidal $CO_2$** improved panic outcomes ( Meuret et al., 2008) |
| (Meuret et al., 2023) | Diving-response task reduced **panic symptoms acutely** (Kyriakoulis & Caballero, 2025) |

FIGURE 3 Foundational papers in the included corpus

### 3.2 Hypercapnia Tolerance

Repeated apnea training shows the clearest effect on physiological tolerance. Free-diving training is associated with stronger diving responses, larger lung and gas stores, and tolerance of higher $PaCO_2$ than seen in non-divers (Kyriakoulis et al., 2021). Two weeks of daily apnea training increased both diving-response magnitude and breath-hold duration (Kyriakoulis et al., 2021).

Shorter and milder training paradigms point in the same direction, though with weaker evidence. One week of pranayama or diaphragmatic breathing increased breath-hold time, and some methods also lowered perceived exertion during breath holding (Shukla et al., 2020). Slow-breathing literature further suggests regular exposure to mild air hunger can increase tolerance of hypercarbia, even though this evidence comes partly from adjacent paradigms rather than pure breath-retention training (Szulczewski, 2019; Bentley et al., 2022).

### 3.3 Panic And Autonomic Response

| Dimension | Breath-Hold Training | Diving-Response Activation | $CO_2$-Targeted Breathing Therapy | Citations |
|---|---|---|---|---|
| **Direct panic evidence** | Sparse, mixed | Acute symptom reduction | Stronger clinical signals | (Roth et al., 1998; Kyriakoulis & Caballero, 2025; Meuret et al., 2008) |
| **Heart-rate effect** | Not consistently reduced | Marked bradycardia | Improved respiratory regulation | (Kyriakoulis et al., 2021; Meuret et al., 2008) |
| **$CO_2$ sensitivity** | Reduced in trained divers | Unclear after single task | Raised $PCO_2$ may desensitize alarm | (Kyriakoulis & Caballero, 2025; Meuret et al., 2023) |
| **Air-hunger tolerance** | Likely improved with repetition | Not directly measured | Exposure to respiratory sensations helps | (Kyriakoulis & Caballero, 2025; Szulczewski, 2019; Meuret et al., 2023) |

| Dimension | Breath-Hold Training | Diving-Response Activation | CO2-Targeted Breathing Therapy | Citations |
|---|---|---|---|---|
| **Clinical certainty** | Low to moderate | Preliminary | Moderate | (Kyriakoulis & Caballero, 2025; Meuret et al., 2008) |

The key distinction is that **acute autonomic calming** is best supported for diving-response maneuvers such as cold facial immersion, whereas **longer-term desensitization to CO2-related fear** is better supported by therapies that explicitly retrain CO2 regulation. Breath retention alone likely contributes to both, but direct longitudinal proof remains thin (Kyriakoulis & Caballero, 2025; Meuret et al., 2008).

### 3.4 Contradictions And Limits

Direct breath-hold challenge studies in panic disorder do not consistently show exaggerated anxiety responses. In one repeated 30-second breath-hold study, panic, generalized anxiety, and control groups had similar anxiety increases and similar autonomic responses, despite lower baseline end-tidal CO2 in panic patients (Roth et al., 1998). Another study found no difference in anxiety increase during breath holding between panic disorder and other anxiety groups, although apnea times tended to be shorter in panic disorder (Zandbergen et al., 1992).

Not all breath-focused interventions improve anxiety more than active controls. A mobile breathing-retraining app failed to show significant decreases in anxiety or panic versus control over four weeks ( Pham et al., 2016). The largest blinded trial of high-ventilation breathwork with retention also found no advantage over an active comparator for stress, anxiety, depression, or wellbeing in healthy adults (Fincham et al., 2024).

### Results Timeline

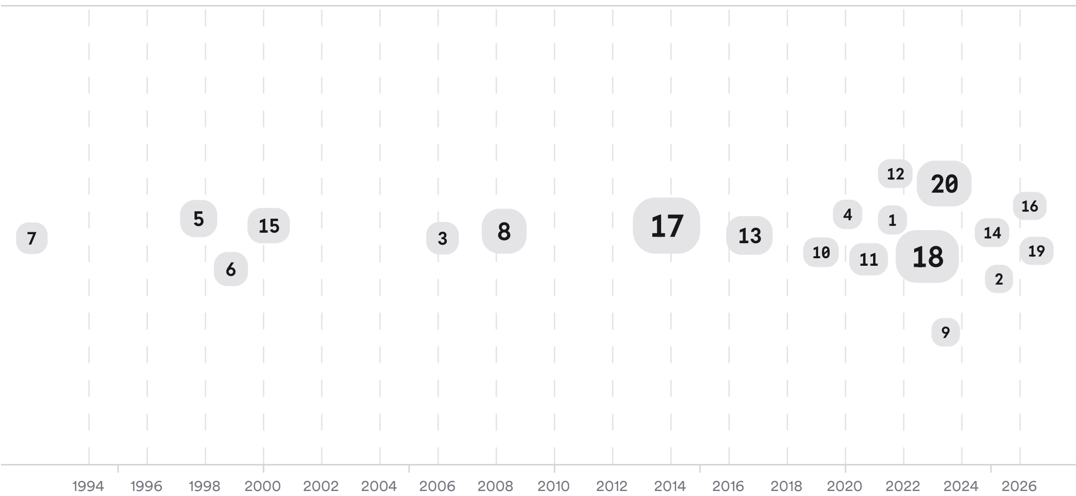


FIGURE 4 Timeline of included studies; larger markers indicate more citations

### Top Contributors

| Type | Name | Papers |
|---|---|---|
| Author | A. Meuret | [efb8f30af39257efb94f297d61bb2229][0f561e2f512b57f49431c306aba06f32] |
| Author | Peter Kyriakoulis | [89938a914da8558db71ccf88e99437c5] [fd944ce4204150a1b0d1142d4302918d] |
| Author | W. Roth | [db797a85f0435fd48dbf62bb67b35c1b] [efb8f30af39257efb94f297d61bb2229] |

| Type | Name | Papers |
|---|---|---|
| Journal | *Frontiers in Psychiatry* | [89938a914da8558db71ccf88e99437c5] [fd944ce4204150a1b0d1142d4302918d] |
| Journal | *Respiratory Physiology & Neurobiology* | [2578ac6995ba5e1da380a79864cdf598] [ffa4a9a69d20506294bbe3f451b1b2ba] |
| Journal | *Psychosomatic Medicine* | [db797a85f0435fd48dbf62bb67b35c1b] [0f561e2f512b57f49431c306aba06f32] |

FIGURE 5 Authors and journals most frequent in included papers

## 4. Discussion

The evidence is strongest for a physiological training effect and weaker for a clinical antipanic effect. Diver studies and apnea-training reports consistently show longer breath-hold times, stronger diving responses, and reduced behavioral or ventilatory sensitivity to $CO_2$ with repeated exposure (Kyriakoulis et al., 2021; Kyriakoulis & Caballero, 2025). That pattern is biologically plausible because breath-hold practice repeatedly exposes participants to rising $CO_2$ and falling $O_2$, conditions that seem to shift the threshold for urge-to-breathe and autonomic response (Kyriakoulis & Caballero, 2025).

The panic question is harder because the relevant evidence comes from several partially overlapping literatures. Panic patients do show greater $CO_2$-triggered suffocation sensations, altered brain responses during voluntary breath holding, and, in some studies, elevated physiological reactivity to respiratory challenges (McIntosh et al., 2020; Rassovsky et al., 2006; Bystritsky et al., 2000). But repeated breath-hold tasks alone have not yet been shown in robust trials to durably blunt panic-autonomic responses. Instead, the best clinical evidence comes from interventions that either activate the diving response acutely or correct hypocapnia and raise end-tidal $CO_2$ over time (Kyriakoulis et al., 2021; Meuret et al., 2008; Meuret et al., 2023).

A key caveat is that not all "breathwork" is physiologically similar. Slow breathing generally increases vagal tone and lowers arousal, whereas hyperventilation-retention protocols can acutely raise sympathetic activation, induce alkalosis, and feel stressful before any adaptation occurs (Trinkūnas et al., 2026; Kox et al., 2014; Fincham et al., 2024). That distinction likely explains why some protocols improve calmness immediately while others fit better with exposure or hormesis models than with direct relaxation (Balban et al., 2023; Fox et al., 2025).

| Claim | Evidence Strength | Reasoning | Papers |
|---|---|---|---|
| Deliberate breath retention **increases hypercapnia tolerance** in trained practitioners. | Strong | Supported by trained-diver physiology and short apnea-training studies, with consistent direction across papers. | (Kyriakoulis et al., 2021; Kyriakoulis & Caballero, 2025) |
| Deliberate breath retention **reduces panic-like autonomic response** to air hunger. | Moderate | Supported indirectly by diving-response and $CO_2$-exposure literatures, but direct longitudinal trials are scarce. | (Kyriakoulis et al., 2021; Szulczewski, 2019; Meuret et al., 2023) |
| Panic disorder involves **heightened $CO_2$-related threat processing.** | Strong | Replicated across $CO_2$ challenge, imaging, and respiratory-reactivity studies. | (Rassovsky et al., 2006; McIntosh et al., 2020; Gorman et al., 1997) |
| Raising low $CO_2$ toward eucapnia **improves panic outcomes** better than nonspecific slow breathing. | Moderate | Clinical RCTs and mechanistic analyses support $PCO_2$ normalization as a plausible target. | (Meuret et al., 2008; Meuret et al., 2023) |

| Claim | Evidence Strength | Reasoning | Papers |
|---|---|---|---|
| Brief remote hyperventilation-retention protocols **improve mental health more than active controls.** | Weak | Largest blinded trial found no between-group benefit on stress or anxiety outcomes. | (Fincham et al., 2024) |

FIGURE 6 Key claims and evidence across included papers

## 5. Conclusion

Overall, practicing deliberate breath retention does appear to increase physiological tolerance to hypercapnia, particularly when repeated over time in apnea-trained people. Whether it also reduces the autonomic panic response associated with air hunger is less certain: the literature supports acute autonomic slowing through diving-response activation and longer-term benefit from CO2-focused retraining, but not yet a strong direct case for breath retention alone (Kyriakoulis et al., 2021; Meuret et al., 2008; Kyriakoulis & Caballero, 2025).

### Research Gaps

The main gap is the absence of large, well-controlled longitudinal trials that isolate deliberate breath retention from adjacent elements such as hyperventilation, cold exposure, meditation, or biofeedback. Current evidence is strongest for mechanism and weakest for clinical translation in panic-prone populations (Kyriakoulis & Caballero, 2025; Fincham et al., 2023).

| Topic/Outcome | Healthy Adults | Panic Disorder | Mechanism | Long-Term Trials |
|---|---|---|---|---|
| Breath-hold duration adaptation | 6 | 2 | 5 | 2 |
| CO2 sensitivity change | 4 | 3 | 4 | 1 |
| Panic symptom reduction | 2 | 4 | 3 | 1 |
| Autonomic markers during air hunger | 4 | 3 | 4 | 1 |

### Open Research Questions

Direct trials now need to test whether repeated breath-retention practice alone, without cold exposure or hyperventilation confounds, changes CO2 tolerance and panic-related autonomic reactivity.

| Question | Why |
|---|---|
| **Does isolated breath-retention training reduce panic symptoms in patients with high CO2 sensitivity?** | This would test the core clinical claim directly in the subgroup most likely to benefit. |
| **What training dose is required for durable reductions in ventilatory and affective responses to hypercapnia?** | Current studies suggest adaptation, but frequency, intensity, and durability remain unclear. |
| **Are improvements driven by CO2 exposure, hypoxia, diving-response conditioning, or expectancy and coping effects?** | Multi-arm mechanistic trials could separate physiological desensitization from cognitive or contextual effects. |

Practicing deliberate breath retention increases hypercapnia tolerance with moderate-to-strong support, but its role in reducing air-hunger panic responses remains promising rather than settled.

### References

Balban, M. Y., Neri, E., Kogon, M. M., Weed, L., Nouriani, B., Jo, B., Holl, G., Zeitzer, J., Spiegel, D., & Huberman, A. (2023). Brief structured respiration practices enhance mood and reduce physiological arousal. *Cell Reports Medicine, 4*. https://doi.org/10.1016/j.xcrm.2022.100895

Bentley, T., Seeber, C., Hightower, E., Mackenzie, B., Wilson, R., Velazquez, A., Cheng, A., Arce, N., & Lorenz, K. (2022). Slow-Breathing Curriculum for Stress Reduction in High School Students: Lessons Learned From a Feasibility Pilot. *Frontiers in Rehabilitation Sciences, 3*. https://doi.org/10.3389/fresc.2022.864079

Bystritsky, A., Craske, M., Maidenberg, E., Vapnik, T., & Shapiro, D. (2000). Autonomic reactivity of panic patients during a CO2 inhalation procedure. *Depression and Anxiety, 11*. https://doi.org/10.1002/(sici)1520-6394(2000)11:1<15::aid-da3>3.0.co;2-w

Chiron, F., Gulören, B., Erblang, M., Poirier, C., Elbaz, M., Servonnet, A., Gaudin, M., Coz, C. L., Lopes, P., Chennaoui, M., Hanon, C., Léger, D., & Thomas, C. (2025). Exploring the Influence of Coherent Breathing on Psychophysiological Stress During a Simulated 3-Day 400-m Race. *Journal of Strength and Conditioning Research, 40*, e460 - e471. https://doi.org/10.1519/jsc.0000000000005377

Fincham, G. W., Epel, E., Colasanti, A., Strauss, C., & Cavanagh, K. (2024). Effects of brief remote high ventilation breathwork with retention on mental health and wellbeing: a randomised placebo-controlled trial. *Scientific Reports, 14*. https://doi.org/10.1038/s41598-024-64254-7

Fincham, G. W., Strauss, C., Montero-Marín, J., & Cavanagh, K. (2023). Effect of breathwork on stress and mental health: A meta-analysis of randomised-controlled trials. *Scientific Reports, 13*. https://doi.org/10.1038/s41598-022-27247-y

Fox, N., Biddell, H., & King, J. B. (2025). A semi-randomised control trial assessing psychophysiological effects of breathwork and cold immersion. *Scientific Reports, 15*. https://doi.org/10.1038/s41598-025-29187-9

Gorman, J., Browne, S., Papp, L., Martinez, J. M., Welkowitz, L., Coplan, J., Goetz, R., Kent, J., & Klein, D. (1997). Effect of antipanic treatment on response to carbon dioxide.. *Biological psychiatry, 42 11*, 982-91. https://doi.org/10.1016/s0006-3223(97)00160-1

Kox, M., Van Eijk, L. T., Zwaag, J., Van Den Wildenberg, J., Sweep, F., Van Der Hoeven, J. G., & Pickkers, P. (2014). Voluntary activation of the sympathetic nervous system and attenuation of the innate immune response in humans. *Proceedings of the National Academy of Sciences, 111*, 7379 - 7384. https://doi.org/10.1073/pnas.1322174111

Kyriakoulis, P., Kyrios, M., Nardi, A., Freire, R., & Schier, M. (2021). The Implications of the Diving Response in Reducing Panic Symptoms. *Frontiers in Psychiatry, 12*. https://doi.org/10.3389/fpsyt.2021.784884

Kyriakoulis, P., & Caballero, C. L. (2025). The implications of the diving response in altering carbon dioxide sensitivity as measured by changes in heart rate, respiration rate and psychological measures in panic disorder patients. *Frontiers in Psychiatry, 16*. https://doi.org/10.3389/fpsyt.2025.1533019

McIntosh, R., Hoshi, R., & Timpano, K. (2020). Take my breath away: Neural activation at breath-hold differentiates individuals with panic disorder from healthy controls.. *Respiratory physiology & neurobiology*, 103427. https://doi.org/10.1016/j.resp.2020.103427

Meuret, A., Wilhelm, F., Ritz, T., & Roth, W. (2008). Feedback of end-tidal pCO2 as a therapeutic approach for panic disorder.. *Journal of psychiatric research, 42 7*, 560-8. https://doi.org/10.1016/j.jpsychires.2007.06.005

Meuret, A., Rosenfield, D., Millard, M., & Ritz, T. (2023). Biofeedback Training to Increase PCO2 in Asthma with Elevated Anxiety: A One-Stop Treatment for Both Conditions?. *Psychosomatic medicine, 85*, 440 - 448. https://doi.org/10.1097/psy.0000000000001188

Pham, Q., Khatib, Y., Stansfeld, S., Fox, S., & Green, T. (2016). Feasibility and Efficacy of an mHealth Game for Managing Anxiety: "Flowy" Randomized Controlled Pilot Trial and Design Evaluation. *Games for Health Journal, 5*, 50 - 67. https://doi.org/10.1089/g4h.2015.0033

Rassovsky, Y., Abrams, K., & Kushner, M. (2006). Suffocation and respiratory responses to carbon dioxide and breath holding challenges in individuals with panic disorder.. *Journal of psychosomatic research, 60 3*, 291-8. https://doi.org/10.1016/j.jpsychores.2005.08.005

Roth, W., Wilhelm, F., & Trabert, W. (1998). Voluntary Breath Holding in Panic and Generalized Anxiety Disorders. *Psychosomatic Medicine, 60*, 671-679. https://doi.org/10.1097/00006842-199811000-00004

Shukla, M., Chauhan, D., & Raj, R. (2020). Breathing exercises and pranayamas to decrease perceived exertion during breath-holding while locked-down due to COVID-19 online randomized study. *Complementary Therapies in Clinical Practice, 41*, 101248 - 101248. https://doi.org/10.1016/j.ctcp.2020.101248

Szulczewski, M. (2019). An Anti-hyperventilation Instruction Decreases the Drop in End-tidal CO2 and Symptoms of Hyperventilation During Breathing at 0.1 Hz. *Applied Psychophysiology and Biofeedback, 44*, 247 - 256. https://doi.org/10.1007/s10484-019-09438-y

Trinkūnas, E., Kairiukstiene, Z., Trinkunaite, M., Poderiene, K., Brazdžionytė, R., & Poderys, J. (2026). Post-Exercise Controlled Breathing Enhances Cardiovascular Recovery and Autonomic Balance: A Randomised Crossover Study.. *Medicina, 62 2*. https://doi.org/10.3390/medicina62020318

Zandbergen, J., Strahm, M., Pols, H., & Griez, E. (1992). Breath-holding in panic disorder.. *Comprehensive psychiatry, 33 1*, 47-51. https://doi.org/10.1016/0010-440x(92)90079-6