A Review and Update on the Biochemical Basis of Conscious Breathing (Pranayama)

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Abstract

Breathing has long been recognised as a vital process in Eastern traditions such as YOGA and Ayurvedic medicine, where *Pranayama* is regarded as a transformative practice that harmonises body and mind. While the East developed sophisticated systems of breath regulation for health and self-awareness, the West largely overlooked their significance until the late 19th and early 20th centuries. A group of pioneering physicians, sometimes referred to as *"the pulmonauts"*, including Christian Bohr, Konstantin Buteyko, and Peter M Litchfield, explored the physiological foundations of respiration. They emphasised the benefits of slow, nasal breathing and its relationship to both physical and emotional well- being. In the 21st century, contemporary researchers and practitioners such as James Nestor, J. Patrick McKeown and Anders Olsson have expanded this understanding through the fields of biochemistry, physiology, and biomechanics.

Their work has clarified the mechanisms underlying conscious breathing and refined ancient *pranayama* techniques. Integrating insights from both Eastern and Western traditions reveals that breathing is a central factor in maintaining homeostasis and emotional balance.

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Introduction

The importance of breathing has long been recognised in Eastern traditions such as YOGA and Ayurveda, a millennial Medicine. The term pranayama comes from Sanskrit, where **prana** means "vital energy" and **ayama** translates as "control" or "expansion." Pranayama is more than just a simple breathing technique; it is a transformative practice that regulates vital energy through conscious breath control (1).

Despite its essential role in health and well-being, breathing has often been overlooked in the West. Between 1870 and 1950, however, a group of physicians known as "the pulmonauts", including *Christian Bohr(1904)(2), Konstantin Buteyko(1923)(3),* studied and promoted healthy breathing habits. They emphasised slow, relaxed, nasal breathing during rest. Research has shown a strong connection between dysfunctional breathing patterns and physical and emotional health. Stressful breathing, for example, can lead to hypoxia (insufficient Oxygen), which in turn affects the brain and generates feelings of anxiety, fear, and distress.

The work of these Western physicians, together with the wisdom of Eastern traditions like Yoga and Ayurveda, and modern practices such as mindfulness and meditation, all highlight the central role of breathing in maintaining the balance of body, mind, and emotions (4). Conversely, in the 21st century, modern Western followers of the Pulmonaut school, such as Olson A. (5), Nestor J. (6), and McKeown P. (7,8), have applied their knowledge of blood chemistry, physiology, anatomy, and the biomechanical mechanisms that underlie conscious breathing. At the same time, they have contributed to a deeper understanding and refinement of pranayama practice.

The purpose of this work is to compile, explain, and actualise these pranayama techniques from a biochemical, physiological and anatomical perspective to facilitate their comprehension and application in alternative medicine.

Materials And Methods

Pranayama (The Science of Conscious Breathing)

Pranayama is a core practice in Yoga that focuses on controlling and expanding vital energy (*prana*) through the breath. Mentioned in Patanjali's Yoga *Sutras*, it is regarded as the fourth limb of Yoga and is designed to prepare both body and mind for deep meditation. The basic practice includes techniques such as abdominal breathing (*Adhama Pranayama*), complete or yogic breathing (*Dirgha Pranayama*), and alternate nostril breathing (*basic Nadi Shodhana*), and advanced techniques such as Anulom Vilom**,** Bhastrika**,** and others, each producing specific effects on balance, energy, and mental calm(1). Their benefits include improved lung capacity, regulation of the nervous system, stress reduction, and enhanced concentration and mental clarity (4). It's recommended to practice in a quiet setting, maintaining good posture and focusing on your breathing. When integrated with asanas and meditation, Pranayama enhances overall well-being and fosters greater physical and mental(9,10)

Physiology of Breathing

The cells and organs of our body constantly consume Oxygen and produce large amounts of carbon dioxide. Breathing is one of our most fundamental functions, as it provides the body with Oxygen while removing carbon dioxide (11). Oxygen enters the lungs through the nasal passages and throat, then passes down the trachea, which branches into increasingly smaller tubes within the lungs, ending in tiny sacs called alveoli. Each alveolus is surrounded by minute blood vessels known as capillaries, which allow Oxygen to pass into the bloodstream while collecting waste products. The alveoli are clustered like bunches of grapes, and each lung contains several hundred million of them. Once the air reaches the lungs, it fills the alveoli, and Oxygen diffuses into the blood, which is carried by haemoglobin in red blood cells to every cell in the body. At the same time, the blood releases carbon dioxide into the alveoli, which is then exhaled. This waste, transported by haemoglobin, leaves the body as the alveoli deflate and empty of the gases they have collected (12,13). During breath holding, following normal breath patterns (inhalation, exhalation, break hold-time), oxygen levels drop, and carbon dioxide levels increase. This causes acidosis in humans by increasing blood CO_2, decreasing blood pH, and reducing oxygen affinity, which facilitates oxygen delivery to tissues. Most importantly, CO_2 determines the bioavailability of Oxygen to the tissues and cells; it is not always a waste gas.

Nose and paranasal sinuses

An essential element in Pranayama is breathing through the nose. From an anatomical point of view, the nose is composed of the external nasal pyramid, the nasal cavities, the nasal septum, the turbinates (superior, middle, and inferior), and the paranasal sinuses (frontal, ethmoidal, sphenoidal, and maxillary)(14,15). The nasal cycle depends on erectile tissue that acts as an air-conditioning system for inspired air, regulating its temperature, humidity, and airflow resistance. In addition, the nasal mucosa produces chemical substances such as nitric oxide (NO), a powerful vasodilator that contributes to normal respiratory function. Breathing through the nose results in a 10-20% increase in oxygen uptake in the blood. During breathing, the nasal cilia move the mucus backward and downward, functioning like a conveyor belt that cleans and filters the inspired air, and represents an important first line of defence against infection. Furthermore, breathing through the mouth leads to greater water loss. Studies show that up to 42% more water is lost during mouth breathing compared to nasal breathing. In contrast, breathing through the nose helps retain moisture and therefore plays an important role in preventing dehydration(8).

Neuromuscular Mechanisms of Respiration: The Diaphragm and the Phrenic Nerve

The diaphragm, often called "the second heart," is the primary muscle responsible for breathing. During inhalation, the diaphragm contracts and moves downward, expanding the lungs and allowing air to enter. During exhalation, the diaphragm relaxes and rises, reducing lung volume and aiding air expulsion (Fig. 1). The phrenic nerve innervates the diaphragm. It originates in the cervical spinal cord and

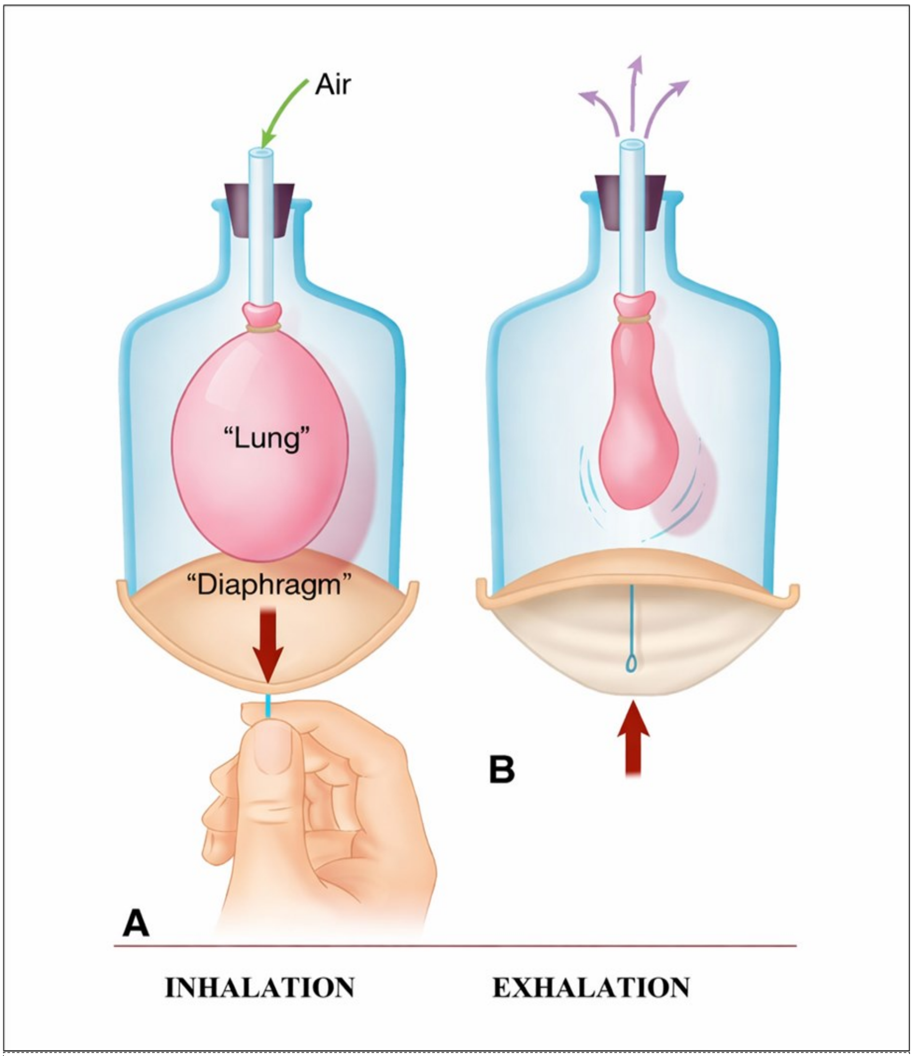

Figure 1. Bell jar experiment showing how we breathe

travels downward to reach the diaphragm, a thin muscle located below the lungs and heart that separates the thoracic and abdominal cavities. Its primary function is to regulate the contraction and relaxation of the diaphragm, thereby controlling the breathing process (14). Forcing exhalation can make the following inhalation deeper and more effective. Under quiet breathing conditions, the diaphragm performs approximately 70-80% of the respiratory work. At the same time, the remaining effort comes from accessory muscles such as the scalenes, external intercostals, sternocleidomastoid, and parasternal intercostals(15).

Acid-Base System: Biochemical Mechanism of Gas Exchange

The human body maintains blood pH within a very narrow range, between 7.35 and 7.45, since even small variations can disrupt essential enzymatic and metabolic processes(11,12). To maintain this acid-base balance, three primary mechanisms work in coordination: plasma buffer systems, the respiratory system, and the renal system.

Buffer systems rapidly neutralise changes in hydrogen and hydroxyl ion concentrations (HCO_3^-); the most important is the bicarbonate buffer, which operates through a chemical reaction(13).

$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-$

The respiratory system helps regulate pH by controlling the amount of carbon dioxide in the blood: when pH decreases (acidosis), breathing rate increases to eliminate CO_2 and reduce carbonic acid, whereas when pH rises (alkalosis), breathing slows down to retain CO_2 and restore balance(11,12). These alterations in blood pH can have significant physiological consequences: severe acidosis may impair enzyme function, reduce oxygen delivery to tissues, and cause symptoms such as confusion, fatigue, and shortness of breath, while severe alkalosis can lead to dizziness, tingling sensations, muscle spasms, and decreased cerebral blood flow. Even subtle shifts in blood pH automatically trigger respiratory adjustments to maintain equilibrium, processes in which the vagus nerve plays a central regulatory role(13).

The renal system regulates pH by excreting hydrogen ions in the urine and adjusting the reabsorption or excretion of bicarbonate. Although it acts more slowly than the respiratory system, it produces a long-lasting effect by restoring and maintaining the body's acid-base balance over time(12). The kidneys secrete erythropoietin (EPO), a hormone released in response to low oxygen levels in the blood. One of EPO's primary functions is to stimulate the production and maturation of red blood cells in the bone marrow, which enhances oxygen delivery to the muscles (13).

In summary, oxygen transport and gas exchange rely on the reversible binding of oxygen to haemoglobin in red blood cells, forming oxyhaemoglobin in the lungs. During inhalation, oxygen reaches the alveoli and diffuses into the bloodstream along its concentration gradient. Carbon dioxide, in contrast, is transported in three main forms: dissolved in plasma (7–10%), bound to haemoglobin (20–30%), and predominantly as bicarbonate ions (60–70%) through the action of the enzyme carbonic anhydrase (11). Haemoglobin's affinity for oxygen is not fixed but is influenced by several physiological factors that modify its molecular conformation. One of the most important is the Bohr effect, whereby a decrease in pH reduces haemoglobin's affinity for oxygen. In acidic conditions, protons bind to haemoglobin, stabilising its tense (T) state, which facilitates oxygen release to the tissues (12). This mechanism is especially relevant in metabolically active tissues, where increased production of carbon dioxide and lactic acid lowers pH and promotes oxygen unloading precisely where demand is highest. In addition to low pH, elevated CO_2 levels, increased temperature, and the presence of 2,3-bisphosphoglycerate (2,3-BPG), a compound synthesised by erythrocytes in response to hypoxia,further reduce haemoglobin's oxygen affinity, enhancing tissue oxygenation, particularly in exercising muscles (12,13).

Although medical education often portrays oxygen as purely beneficial and carbon dioxide as harmful, physiological evidence shows that an adequate concentration of carbon dioxide in the blood is essential for maintaining normal health and effective oxygen delivery (8). Most importantly, carbon dioxide plays a key role in regulating the availability of Oxygen to tissues and cells. In other words, carbon dioxide should not be considered merely a waste gas. Some authors even advocate carbon dioxide–based therapies, giving rise to schools of thought aligned with these therapies(5,16,17).

Vagus Nerve: Physiology and Biochemical Mechanisms

The vagus nerve, also known as the tenth cranial nerve (CN X), originates in the brainstem, the lowest part of the brain, and extends through multiple branches that reach the heart, respiratory system, and gastrointestinal tract, continuing down to the deepest viscera of the abdomen. Approximately 80–90% of its fibres are afferent, meaning they transmit information from the body to the brain, while the remaining efferent fibres innervate organs such as the heart. The vagus nerve, therefore, forms an essential communication link between the brain, heart, and lungs(18). It regulates vital processes such as heart rate, respiration, and digestion, and numerous studies have shown its positive influence on physical, mental, and cognitive well-being(19). Vagus nerve activity helps counteract excessive levels of cortisol, the stress hormone responsible for the fight-or-flight response(20). The main neurotransmitter associated with the vagus nerve is acetylcholine(12,13), which plays a crucial role in regulating the body's autonomic functions. By releasing acetylcholine, the vagus nerve slows the heart rate, stimulates digestion, and balances the effects of the sympathetic system (18). *The* **Heart Rate Variability Test (HRV***), middle vagal tone, measures the difference between consecutive heartbeats and is controlled by the autonomic nervous system (ANS) (21). The* HRV is measured using devices that record heart activity, such as validated wearable devices (e.g., smartwatches). These devices detect the time between successive heartbeats and calculate variability using specialised software. Controlled breathing techniques, such as Pranayama, can stimulate the vagus nerve, activate the parasympathetic nervous system, reduce heart rate, and improve heart rate variability (HRV), a key indicator of stress resilience (22). These practices also help regulate blood pH by modifying ventilation and blood flow(23).

Physiological Control of Breathing and Blood Pressure: The Roles of Chemoreceptors and the Baroreflex

Breathing and blood pressure are controlled by chemoreceptors and the baroreflex(24). Chemoreceptors detect changes in Oxygen and carbon dioxide levels in the blood. When CO_2 increases, breathing becomes faster and deeper; when CO_2 decreases, breathing slows. This helps keep the body in balance. Blood pressure is regulated by the baroreflex, using receptors in the aorta and carotid arteries. High blood pressure slows the heart rate and relaxes blood vessels, while low blood pressure increases heart rate and constricts blood vessels. Breathing and heart rate are closely connected(25). Their coordination improves oxygen exchange, heart rate variability, and nervous system balance. Chemoreceptors also interact with brain areas involved in emotion, such as the amygdala. Certain practices, such as controlled breathing techniques like Pranayama, may improve vagal tone and chemoreceptor balance. Interestingly, stimuli such as spicy foods, acupuncture, and breathing practices are thought to increase "prana," enhancing vagal and chemoreceptive balance(24). For example, breath holding after exhalation increases CO_2 levels in the blood, enhancing oxygen release from red blood cells to body tissues. With practice, sensitivity to carbon dioxide decreases, and breath-hold capacity improves(26). Historically, mixtures of 20% CO_2 and 70% O_2 were used therapeutically to treat anxiety, panic, and schizophrenia(16,17).

Advanced breathing techniques of Pranayama

Kapalabhati, or skull-shining breath, is characterised by rapid, forceful exhalations with passive inhalations, which quickly expel CO_2 and induce a temporary respiratory alkalosis; it also enhances cerebral oxygenation, stimulates the central nervous system, and may help relieve metabolic fatigue(27)

Anulom Vilom, or a variant of Nadi Shodhana, is a breathing technique derived from Nadi Shodhana and commonly referred to as alternate-nostril breathing. It consists of a controlled cycle of inhalation through one nostril, brief breath retention, and exhalation through the opposite side. This pattern encourages mild carbon dioxide retention, supports physiological pH stability, and contributes to stress reduction by balancing sympathetic and parasympathetic nervous system activity. Functional differences between nostrils have been documented: airflow through the right nostril is linked to increased sympathetic dominance, reflected in elevated heart rate, arterial pressure, and cortisol secretion, as well as greater engagement of the left prefrontal cortex, an area associated with imaginative and creative processing and heightened emotional reactivity. In contrast, the predominance of left-nostril breathing favours parasympathetic regulation, facilitating relaxation responses, lowering cardiovascular parameters, and alleviating anxiety, while preferentially activating right-hemisphere networks involved in linguistic, logical, and quantitative functions (28).

Bhastrika, also known as bellows breathing or Breath of Fire, consists of rapid and forceful inhalations and exhalations that markedly increase pulmonary ventilation. This heightened breathing pattern enhances oxygen intake but simultaneously accelerates CO_2 elimination, producing an energising effect. However, excessive or prolonged practice may lead to hypocapnia ($PCO_2 < 35$ mmHg) (29), which can result in respiratory alkalosis, dizziness, cerebral vasoconstriction, and transient cerebral hypoxia (30).

Kumbhaka, or breath retention is a pranayama technique that involves the conscious retention of the breath,following inhalation or exhalation, temporarily increases CO_2 levels, stimulates the Bohr effect, enhances oxygen release to tissues, and may induce a profound sense of calm. (30).

Ujjayi pranayama is a yogic breathing technique characterised by slow, deep inhalations and exhalations through the nose, with a gentle contraction of the glottis. This creates a soft, steady sound similar to ocean waves. It is used to calm the mind, enhance concentration, and regulate breathing rhythm, and is commonly practiced during asana practice and meditation (4,10).

Bhramari Pranayama (Bee Breath) is a calming breathing technique where one inhales deeply through the nose and exhales while producing a humming sound like a bee. It helps reduce stress, anxiety, and mental tension, improves focus, and promotes relaxation and better sleep(4,10)

Tibetan pranayama, commonly known as **tummo breathing**, is characterised by slow, controlled nasal breathing combined with breath retention and deliberate activation of the abdominal and pelvic musculature. This practice has been shown to increase body temperature through thermogenesis while preserving or elevating arterial CO_2 levels. The controlled hypoventilation inherent to tummo enhances tolerance to CO_2 and facilitates oxygen release to tissues via the Bohr effect, particularly in metabolically active regions(29).

Results

Pranayama, a core practice of Yoga focused on conscious breath control, has a significant effect on human physiology, particularly on acid-base balance and homeostasis. By modifying breathing rate and depth, Pranayama regulates carbon dioxide (CO_2) levels and blood pH. Rapid breathing techniques increase CO_2 exhalation, leading to hypocapnia and a mild respiratory alkalosis. In contrast, slow promotes CO_2 retention, inducing mild respiratory acidosis and enhancing oxygen release to tissues through the Bohr effect.

Pranayama is a non-invasive technique that can be applied in various clinical situations: **In arterial hypertension**, which is associated with autonomic imbalance and oxidative stress, both linked to cellular pH alterations, technique such as and Nadi Shodhana or Bhramari Pranayama activate the parasympathetic system, reduce blood pressure, improve oxygenation, and stabilise pH. Severals clinical trials, reporting significant reductions in both systolic and diastolic pressure(31**).** In conditions such as **diabetic ketoacidosis** , characterised by severe metabolic acidosis resulting from the accumulation of ketone bodies, respiratory physiology plays a critical compensatory role. During the acute phase, hyperventilation is an essential mechanism that facilitates the elimination of carbon dioxide (CO_2), Bhastrika breathing and helps limit further reductions in blood pH. Through these indirect mechanisms, controlled breathing practices may support long-term metabolic homeostasis and improved glycaemic control. (32,33). **In cardiovascular diseases** such as chronic heart failure, which are associated with tissue hypoxia and metabolic acidosis due to reduced blood flow. Controlled breathing techniques, such as Ujjayi or Bhramari Pranayama enhance oxygenation and optimise gas exchange by reducing the respiratory rate, which in turn decreases cardiac workload and helps stabilise acid-base balance. (31). **In obstructive sleep apnea(OSA)**, which is characterised by recurrent interruptions of breathing during sleep that result in hypercapnia, hypoxia, and fluctuations in blood pH. Diaphragmatic and conscious deep breathing as Ujjayi pranayama can enhance respiratory muscle control and reduce the frequency of apnea episodes by promoting more stable breathing patterns. Slow, deep breathing has also been shown to increase vagal tone, thereby improving sleep quality. In addition, slow, controlled breathing may stimulate melatonin production, an essential sleep-inducing hormone that has been shown to enhance vagal tone further and inhibit sympathetic nervous system activation (34). **Asthma, COPD (Chronic obstructive pulmonary disease) and some allergic diseases:** characterised by breathing difficulty. During symptoms, patients may breathe excessively, leading to hyperventilation and a reduction in blood carbon dioxide (CO_2) levels. This can cause vasoconstriction, reduced oxygen delivery to the brain, and increased brain excitability and anxiety. Nasal breathing and the Buteyko method, Ujjayi pranayam, or wearing MyoTape (6), will help bring the lips together to ensure nasal breathing**,** which aims to reduce hyperventilation**,** encourage nasal breathing**,** and promote slow, gentle, and controlled breathing. This may help improve symptom control when used alongside appropriate medication. **In chronic pain and inflammatory conditions** such as rheumatoid arthritis, which are linked to chronic inflammation, oxidative stress, and local pH alterations, Ujjayi breathing supports mitochondrial function and cellular oxygenation, stabilises pH, and reduces oxidative stress through parasympathetic activation(35). **Renal insufficiency**: gentle breathing practices such as slow, deep breathing, Nadi Shodhana (performed without breath retentions), and mild Bhramari pranayama may be considered as complementary interventions in clinically stable patients with chronic kidney disease. These techniques may help reduce psychological stress, support autonomic nervous system balance, and improve overall quality of life. **Dysfunctional Breathing Syndrome**: This syndrome encompasses a range of conditions affecting the neuromusculoskeletal system and the biomechanical function of the diaphragm, including disorders such as low back and neck pain, scoliosis, kyphosis, and pelvic floor dysfunctions, as well as neuromuscular and neurodegenerative diseases such as amyotrophic lateral sclerosis (ALS), Parkinson's disease, multiple sclerosis, and various muscular dystrophies. These alterations may compromise regulation of intra-abdominal pressure (IAP), lead to inefficient breathing patterns such as hyperventilation, and cause physiological imbalances (respiratory alkalosis, hypercapnia, and hypoxia), resulting in symptoms such as fatigue, headaches, dizziness, and dyspnea (29). Advanced breathing control techniques, such as the Buteyko method, are useful as adjuncts to physical and postural rehabilitation and, together with specific pharmacological treatment, may improve respiratory parameters.Furthermore, **during intense exercise**, when lactic acid accumulation can induce transient metabolic acidosis, fatigue, and decreased performance, post-exercise breathing practices such as slow, deep breathing and gentle forms of advanced techniques like Ujjayi pranayama (performed without breath retentions) can accelerate the recovery of acid-base balance, improve muscle oxygenation, and reduce metabolite accumulation(13,23). Finally**, in cases of anxiety, panic**, and stress-related disorders, anxiety-induced hyperventilation can lead to respiratory alkalosis, producing symptoms such as dizziness, tingling, and shortness of breath. Clinical research has shown that breathing techniques such as Anulom Vilom and slow, deep breathing help restore acid-base balance by normalising CO_2 levels, reduce sympathetic hyperactivity, and significantly decrease both the frequency and intensity of panic attacks (17,30). *An e*xercise to help stop a panic attack*: **Breathing into Cupped Hands**. At the first sign of a panic attack, cup your hands across your mouth and nose and gently slow down your breathing (Fig. 2). If you can breathe slowly and low with lateral expansion and contraction of the lower ribs, then great. Otherwise, concentrate on breathing slowly. Cupping your hands will trap* CO_2 *from your exhaled breath, allowing you to rebreathe* it *back into your lungs. This will increase* CO_2 *in the blood, which will improve blood flow and oxygen delivery to your brain(30)*. A moderate elevation in carbon

Figure 2. Exercise to help stop a Panic Attack: breathing into cupped Hands

Figure 3. Exercise to help stop a Panic Attack: Breathing through a bag

dioxide tension facilitates oxygen release to cerebral tissues via the Bohr effect, thereby promoting physiological relaxation(30).However, the traditional practice of **breathing into a paper bag** (Fig 3) presents significant clinical limitations (36). Re-inhalation of exhaled air may result in hypoxemia and an unregulated rise in CO_2, potentially leading to syncope, cognitive impairment, and exacerbation of symptoms, particularly in individuals with underlying respiratory or cardiovascular disease. However, in non-clinical settings, the paper bag technique is still used in extreme situations despite the aforementioned clinical limitations.In addition, there are therapies based on breath retention and training with different concentrations of CO_2. For instance, exposure to 30% PCO_2 can trigger a panic attack, whereas lower concentrations (15% or even 7%) are used to train chemoreceptors without significantly affecting oxygen levels(16,17,26).

Vagus nerve stimulation (VNS) through prolonged exhalation has been shown to provide significant benefits for physical, mental, and cognitive health. It can reduce anxiety and depression, modulate immune function, inhibit inflammation, and promote both physiological balance and emotional regulation (18, 19). The test HRV, which measures the variability between consecutive heartbeats, is widely regarded as a reliable indicator of vagal tone and autonomic nervous system balance. (21,22) Slow breathing at a rate of 4.5 to 6.5 breaths per minute has been shown to optimise sympathovagal balance, creating an ideal balance between sympathetic and parasympathetic activity (37). Researchers also propose that enhancing vagal tone may help explain the connection between breathing and emotional regulation (9). Independent vagal stimulation, through various pathways, is currently being explored as a therapeutic strategy for several neurological conditions, including autism and other neurodivergent disorders, such as through neuro-fascial release techniques (20). In 2017, Dr Singh reported that CO_2 stimulates the vagus nerve and acts as a natural sedative; insufficient CO_2 may therefore contribute to anxiety, depression, and irritability. He even describes carbon dioxide as "the breath of life" (38).

Furthermore, Pranayama, an accessible and non-invasive practice, has gained increasing attention as a therapeutic complement for clinical conditions that affect acid-base balance. It enhances oxygenation and cellular energy efficiency by improving oxygen saturation, particularly in poorly ventilated lung regions, through slow, deep breathing. Breath retention (Kumbhaka) further optimises oxygen uptake by prolonging haemoglobin-oxygen interaction. In addition, Pranayama supports acid-base homeostasis during stress by reducing sympathetic activation, oxidative stress, and stress-induced acidosis(39). Under conditions such as intense exercise or ketoacidosis, it may facilitate recovery by promoting CO_2 elimination and regulating hydrogen ion production. Techniques such as Nadi Shodhana contribute to pH stability by balancing sympathetic and parasympathetic activity, thereby supporting overall physiological homeostasis. These therapeutic applications, however, must be accompanied by safety considerations: prolonged hyperventilation with techniques such as Kapalabhati or Bhastrika should be avoided to prevent dizziness or cerebral hypoxia; practices must be adapted for patients with severe renal or respiratory failure and for beginners. Should start gradually with gentle techniques such as Nadi Shodhana before progressing to more intense methods(27).

Discussion

Breathing, beyond its basic physiological function, profoundly influences the neurological, cardiovascular, endocrine, and mental health systems. Because breathing is an innate bodily function which most of us take for granted, it only gets our attention when something goes wrong. Scientific evidence shows that both the breathing pattern and the dominant nostril can directly modulate the activity of the autonomic nervous system (23). Right-nostril breathing is associated with sympathetic activation, increasing heart rate, blood pressure, and cortisol levels. It also stimulates the left prefrontal hemisphere, linked to creativity and imagination, as well as to greater sensitivity to negative emotions. Conversely, left-nostril breathing activates the parasympathetic system, promoting relaxation, lowering blood pressure, and reducing anxiety, while enhancing right-hemisphere activity associated with logic, language, and analytical reasoning (28). Nasal breathing offers multiple advantages. It filters and conditions inhaled air, stimulating the production of nitric oxide (NO). This potent bronchodilator enhances oxygen absorption by up to 18% and increases PCO_2 (Partial pressure of Carbon dioxide), promoting vasodilation and optimising gas exchange (23). In addition, breathing through the nose helps retain moisture and therefore plays an important role in preventing dehydration(8).

From a biochemical standpoint, the rhythm and depth of breathing directly influence carbon dioxide (CO_2) homeostasis and the body's acid-base balance. Excessive breathing causes CO_2 loss, shifts blood pH toward alkalosis, and promotes the excretion of minerals by the kidney, such as calcium, magnesium, and potassium(12). In contrast, slower, controlled breathing elevates CO_2, lowers pH, and enhances oxygen release to tissues through the Bohr effect, thereby optimising cellular metabolism(13).

In addition, haemoglobin's affinity for Oxygen depends on pH, CO_2, temperature, and 2,3- bisphosphoglycerate (2,3-BPG). In acidic environments such as metabolically active tissues, where CO_2 and lactic acid accumulate, haemoglobin releases Oxygen more readily. CO_2 facilitates this process by forming carbonic acid or binding to haemoglobin to form carbaminohemoglobin(11). Meanwhile, 2,3-BPG, produced during glycolysis in red blood cells, further regulates oxygen delivery: elevated levels (as in hypoxia or high altitude) promote oxygen release. In contrast, reduced levels make haemoglobin retain Oxygen more tightly(13). This entire mechanism is integrated with the bicarbonate-carbonic acid buffer system, maintained by the lungs and kidneys, which stabilises blood pH within the physiological range of 7.35–7.45(12,13).

The relationship between breathing and biochemical metabolism becomes especially evident during physical exercise. Increased glucose oxidation raises CO_2 production, intensifying acid-base adjustments and oxygen delivery. Nasal breathing during exertion enhances recovery, lowers heart rate, reduces lactic acid buildup by up to 40%, and improves endurance(28). Additionally, the rise in muscle temperature facilitates Oxygen unloading, ensuring adequate supply to energy-demanding tissues. Chronic mouth breathing is associated with a range of structural and functional alterations that adversely affect respiratory efficiency and sleep physiology. These include craniofacial changes such as mandibular retraction, dental malocclusion (including overbite and crowding), airway and sinus obstruction, recurrent sinusitis, and headaches, all of which may compromise cerebral oxygenation. Studies show that up to 42% more water is lost during mouth breathing compared to nasal breathing. During sleep, particularly during REM phases, these alterations can disrupt sleep quality and interfere with endocrine regulation, notably by impairing vasopressin secretion (34).

From a therapeutic perspective, conscious breathing characterised by nasal inhalation, diaphragmatic activation, and a slow, regular, silent rhythm is fundamental for optimising respiratory function. Techniques such as Tough's orthophonic respiratory coordination and the 4-7-8 technique (inhaling for 4 seconds, holding for 7, and exhaling for 8 seconds) are proven effective in reducing chronic hyperventilation and improving overall well-being. However, this method can also be used temporarily to help individuals quickly recover their breath when needed(40). Similarly, devices like Myobrace(41), designed to correct mandibular posture, show promise in restoring proper nasal breathing. In addition ,lung capacity naturally declines with age by approximately 12% in men and up to 30% in women, but targeted practices can counteract this trend (42,43). Free diving, for instance, can increase lung capacity by up to 30%, while regular aerobic exercise improves it by around 15% (44).

Breathing less, through the nose and with prolonged exhalations, elevates PCO_2, enhances aerobic endurance, and boosts cardiorespiratory capacity (VO_2 max). The optimal breathing rhythm is considered to be about 5.5 breaths per minute, with inhalations and exhalations lasting roughly 5.5 seconds each (37). Fundamentally, breathing acts as a true switch of the autonomic nervous system. Rapid, shallow breathing activates the sympathetic branch associated with stress and alertness, whereas prolonged exhalations reinforce parasympathetic dominance, fostering calm. This dynamic is tightly connected to metabolism: during aerobic activity, the ideal heart rate remains below the threshold calculated as 180 minus age (180-Age in years)(43). Once surpassed, anaerobic metabolism predominates, with increased glucose consumption and lactate production. Accelerated breathing reduces PCO_2 (hypocapnia), shifts blood pH toward alkalosis, and promotes the loss of essential minerals and produces various symptoms, including fatigue, headaches, dizziness, sleep disturbances, and a sensation of breathlessness (13,30). Conversely, restrained breathing raises PCO_2, lowers pH, and facilitates oxygen release via the Bohr effect(12). However severe acidosis may impair enzyme function, reduce oxygen delivery to tissues, and cause symptoms such as confusion, fatigue, and shortness of breath.

In addition, reduced CO_2 levels can also cause cerebral ischemia (diminished blood flow) and hypoxia (oxygen deficiency). Even a drop of just 1 mmHg in PCO_2 can decrease cerebral circulation by 2%, and a 22 mmHg in PCO_2, decrease can reduce it by up to 40%, leading to dizziness, tingling, confusion, psychosomatic sensations, or hypnagogic states, those transitional experiences between wakefulness and sleep. (29,30).During breath holding, oxygen levels decline while CO_2 levels increase, leading to mild acidosis due to elevated blood CO_2 and a decreased pH. This reduction in haemoglobin's oxygen affinity enhances oxygen delivery to tissues, an expression of the Bohr effect(11,13).

To sum up, breathing less frequently, through the nose, and with prolonged exhalations enhances respiratory efficiency, maintains acid-base balance, optimises oxygen delivery, regulates the nervous system, and supports long-term health. In particular. For everyday life, a slightly slower and more balanced breathing pattern of around 4-5 breaths per minute is considered most appropriate, this respiratory rate optimises the synchronisation between breathing and heart rate, as been shown in addition to increasing heart rate variability, further promoting positive cardiovascular and nervous system balance. Taken together, these principles reveal that breathing is not merely an automatic mechanical act, but a powerful regulator of biochemistry, physiology, and mental state (23). The focus is on breathing holistically: light, slow, and deep.

Conclusions

In summary, the benefits of Pranayama encompass both physical and mental aspects, making it an essential practice for overall well-being.

Physical benefits: Regular practice improves lung capacity, strengthens the respiratory system, and regulates the nervous system, helping to balance bodily functions and promote better overall health.

Mental health benefits: Pranayama is an effective tool for reducing stress, enhancing concentration, and promoting mental clarity, providing a sense of calm and emotional stability.

Furthermore, breathing represents a unique physiological interface where multiple regulatory systems converge. It is simultaneously governed by autonomic control mechanisms and capable of voluntary modulation, creating a functional gateway between unconscious homeostatic processes and conscious behavioural influence. This bidirectional function positions it as a central regulatory axis through which individuals can exert measurable effects on autonomic activity, emotional regulation, and overall physiological equilibrium. The focus is on breathing holistically: light, slow, and deep, which influences the body's biochemistry and biomechanics and engages the autonomic nervous system. To sum up, **"Breathe light to breathe right".**

Abbreviations

CO_2: Carbon dioxide; NO: Nitric oxide; HCO_3^-: Hydroxyl ion; H_2CO_3:Bicarbonate bufffer; pH: Potential of Hydrogen; EPO: Erythropoietin hormone; (2,3-BPG): 2,3-bisphosphoglycerate; CNX: tenth cranial nerve; HRV: Heart Rate Variability test; OSA: Obstructive sleep apnea; COPD: Chronic Obstructive Pulmonary Disease; IAP: Intra-abdominal pressure; VNS: Vagus nerve Stimulation; REM: Rapid Eye Movement; BOLT test: (Body Oxygen Level Test); VO2: Cardiorespiratory capacity; PCO_2: Partial pressure of CO_2; PO2: Parcial Pressure of O_2; BE: Base Excess; SO_2: Arterial O_2 saturation; Vt: Tidal Volume; RR: Respiratory rate; MV: Minute Ventilation; ASN: Autonomic Nervous System; PSN: Parasympathetic Nerve System.

Authors' contributions

Both authors made valuable contributions to this manuscript. Each author drafted specific sections, and both actively participated in revising the entire document.

Declaration of AI Use

ChatGPT, an OpenAI language mode (version GPT-5.2, 2025),was used to support the writing process and improve clarity in certain article sections. It was not used to generate or alter the research results.

Conflicts of interest

Each author declares that they have no commercial associations (e.g., consultancies, stock ownership, equity interest, patent/licensing arrangement, etc.) that might pose a conflict of interest in connection with the submitted article.

Appendix 1

Normal Values of Arterial Blood Gas and Medical Terminology

- pH:7.35 – 7.45
- PCO_2 (partial pressure of CO_2):35 – 45 mmHg
- PO_2 (partial pressure of O_2):80 – 100 mmHg
- HCO_3^- (bicarbonate):22 – 26 mEq/L
- Base Excess (BE):–2 to +2 mEq/L
- SO_2 (arterial O_2 saturation):95 – 100 %

pH (acidosis<7.35) (Respiratory acidosis, metabolic acidosis)

- Mild acidosis: pH 7.30 – 7.34
- Moderate: pH 7.20 – 7.29
- Severe: pH < 7.20

pH (Alcalosis>7.45). (Respiratory alkalosis, metabolic alkalosis)

- Mild alcalosis: pH 7.46 – 7.50
- Moderate: pH 7.51 – 7.60
- Severe: pH > 7.60

A pH below 6.8 or above 7.8 is usually incompatible with life if not corrected promptly.

PCO_2 (partial pressure of CO_2):35 – 45 mmHg

- Mind Hypocapnia < 35 mmHg (e.g., hyperventilation)
- Moderate Hypercapnia >45 mmHg
- Severe Hypercapnia >60 mmHg.

Critical values <20 or >70 mmHg

PO_2 (arterial partial pressure of Oxygen):80 – 100 mmHg

- Mild hypoxemia< 80 mmHg
- Moderate hypoxemia< 60 mmHg
- Severe hypoxemia, critical condition < 40 mmHg

Arterial oxygen saturation (SO_2):95 – 100 %

- < 90 % → significant hypoxemia.

VO_2 max: index of cardiorespiratory capacity. Reference VO_2 max values in adults:

- Young men (20–29 years) Very low: < 35 ml/kg/min/Average: 40–50 ml/kg/min/Excellent: > 55–60 ml/kg/min
- Young women (20–29 years): Very low: < 27 ml/kg/min/Average: 30–40 ml/kg/min/Excellent: > 45–50 ml/kg/min

In endurance athletes, values may exceed 70–80 ml/kg/min in men and 60–70 ml/kg/min in women.

With age, VO_2 max tends to decline progressively. Factors such as genetics, training, body composition, and altitude influence the results.

Tidal volume (Vt) is the normal volume of air entering the lung during one inhalation at rest (500 ml)

Respiratory rate (RR): The number of breaths per minute(bpm)(12-20 bpm)

Minute ventilation (MV) is the volume of air that enters the lungs during one minute(respiratory rate multiplied by tidal volume): RR x Vt = MV.

Example 12 bpm, a 6 bpm increase del 20% breathing efficiency

Heart Rate Variability (HRV)*(21,22). Heart rate variability(HRV) is a useful index of well-being and resilience. Good HRV indicates a healthy balance in the autonomic nervous system and is indicative of good health. The heartbeats changed constantly, and the more coherent the fluctuations are in speed and insensitivity, the healthier you are likely to be, both mentally and physically. Its oscillations are complex and constantly changing. The cardiovascular system needs to adjust to external and internal stimuli to maintain homeostasis. The HVR measures the difference between consecutive heartbeats and is controlled by the autonomic nervous system(ANS). Growing evidence associates an ANS imbalance with a higher prevalence of disease and death, making HRV a useful tool in predicting and assessing illnesses. HRV low can be caused by stress, emotional distress, and chronic stress, which directly impact wellness. HRV declines significantly with poor health, high cortisol, and low HRV. The HRV middle vagal tone and heart rate variability, along with slow breathing at 4.5 to 6.5 breaths per minute, have been found to optimise sympatho-vagal balance, creating an ideal balance between the two branches of the autonomic nervous system. Because it is closely connected to the functioning of the ANS, especially the parasympathetic Branch (PNS), HRV is considered a reliable measure of how well the vagus nerve is functioning, providing doctors with a way to quantify stress and physical vulnerability to stress.* HRV is measured using devices that record heart activity, such as validated wearable devices (e.g., smartwatches). These devices detect the time between successive heartbeats and calculate variability using specialised software. (Mindfield eSense Pulse HRV Biofeedback, Garmin HRM 600, Garmin HRM 200, PLUX Biosignals HRV)

The BOLT test (Body Oxygen Level Test) is a simple, dynamic test that provides feedback on how efficiently you breathe (7,8). The test consists of exhaling normally through the nose, pinching the nose to hold the breath, and timing how many seconds pass until a definite physical urge to breathe appears. A normal BOLT score ranges between 20 and 40 seconds. A score below 15 seconds strongly suggests a dysfunctional breathing pattern. The goal is to reach a BOLT score of 40 seconds. The BOLT test measures how long you can comfortably hold your breath and reflects your tolerance to carbon dioxide. A low BOLT score indicates that the breathing receptors are overly sensitive to carbon dioxide. An ideal minimum score is around 20 seconds, while scores closer to 40 seconds indicate a better match between breathing volume and metabolic demands. Higher carbon dioxide tolerance enhances the release of Oxygen from the blood to tissues and organs, which increases VO_2 max, improves endurance, and reduces the risk of injury. Additionally, breath-holding can stimulate the spleen to release red blood cells into the circulation

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