Intermittent hypoxia and neurorehabilitation

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Gonzalez-Rothi EJ, Lee KZ, Dale EA, Reier PJ, Mitchell GS, Fuller DD. Intermittent hypoxia and neurorehabilitation. J Appl Physiol 119: 1455–1465, 2015.—In recent years, it has become clear that brief, repeated presentations of hypoxia [i.e., acute intermittent hypoxia (AIH)] can boost the efficacy of more traditional therapeutic strategies in certain cases of neurologic dysfunction. This hypothesis derives from a series of studies in animal models and human subjects performed over the past 35 yr. In 1980, Millhorn et al. (Millhorn DE, Eldridge FL, Waldrop TG. Respir Physiol 41: 87-103, 1980) showed that electrical stimulation of carotid chemosensitive neurons produced a persistent, serotonin-dependent increase in phrenic motor output that outlasts the stimulus for more than 90 min (i.e., a “respiratory memory”). AIH elicits similar phrenic “long-term facilitation” (LTF) by a mechanism that requires cervical spinal serotonin receptor activation and de novo protein synthesis. From 2003 to present, a series of studies demonstrated that AIH can induce neuroplasticity in the injured spinal cord, causing functional recovery of breathing capacity after cervical spinal injury. Subsequently, it was demonstrated that repeated AIH (rAIH) can induce recovery of limb function, and the functional benefits of rAIH are greatest when paired with task-specific training. Since uncontrolled and/or prolonged intermittent hypoxia can elicit pathophysiology, a challenge of intermittent hypoxia research is to ensure that therapeutic protocols are well below the threshold for pathogenesis. This is possible since many low dose rAIH protocols have induced functional benefits without evidence of pathology. We propose that carefully controlled rAIH is a safe and noninvasive modality that can be paired with other neurorehabilitative strategies including traditional activity-based physical therapy or cell-based therapies such as intraspinal transplantation of neural progenitors.

intermittent hypoxia; neurorehabilitation; spinal cord injury; cellular transplantation

THE FUNDAMENTAL THEME OF THIS review article is that brief, repeated presentations of hypoxia [i.e., acute intermittent hypoxia (AIH)] are a safe and (relatively) easily applied therapeutic modality that triggers beneficial neuroplasticity. Although we will focus on potential applications of AIH to neurorehabilitation after spinal cord injury (SCI), the fundamental principles of AIH-induced neuroplasticity are likely to apply to other movement disorders (65, 77). Here, we review evidence that repetitive AIH provides direct benefits to respiratory and nonrespiratory motor function and discuss the potential use of AIH in conjunction with other treatment modalities, including electrical stimulation of the spinal cord and cell-based therapies (i.e., cell transplantation). Like all therapeutic agents, the dose-response curve must be carefully considered. A guiding principle of this article is that appropriate “doses” of AIH evoke beneficial plasticity while minimizing negative consequences associated with more severe or prolonged protocols of intermittent hypoxia (73). Indeed, chronic intermittent hypoxia can lead to a range of pathophysiological outcomes. Thus one challenge in intermittent hypoxia research is to ensure that the AIH paradigm is well below the threshold for pathogenesis.

BRIEF HISTORY OF AIH AND RESPIRATORY MOTOR PLASTICITY

Initial studies of AIH and neuroplasticity focused exclusively on the respiratory system. A timeline that highlights key advances over the past 35 yr is shown in Fig. 1. The seminal work from Millhorn et al. (64) showed that electrical stimula-
tion of carotid chemoefferent neurons (from the primary hypoxia-sensitive chemoreceptors, the carotid bodies) produced a persistent increase in phrenic motor output in anesthetized cats. This study elaborated the concept of long-lasting “memories in breathing,” a topic formally reviewed in 1986 in the Handbook of Physiology (20). Subsequently, Hayashi et al. (37) showed that similar neuroplasticity could be evoked by replacing electrical stimulation of the carotid sinus nerve with AIH. In this paper, the term “long-term facilitation” (LTF) was introduced to describe the persistent increase of phrenic nerve burst amplitude that occurred after exposure to brief periods of intermittent hypoxia. Shortly thereafter, Fregosi and Mitchell (26) used electrical stimulation of the carotid sinus nerve in cats to show that LTF also occurs in inspiratory intercostal nerve activity. A few years later, Bach and Mitchell (4) showed that AIH-induced phrenic LTF in rats required activation of serotonin receptors and was also expressed in upper airway motor outputs, particularly in hypoglossal nerve activity. Other notable advances in the AIH/LTF field include the following: 1) establishing that, whereas acute intermittent exposures to hypoxia (i.e., AIH) evokes LTF, exposure to a comparable duration of continuous hypoxia does not (7); 2) a series of papers (using in vivo and in vitro preparations) localizing the relevant cellular mechanisms at or near the specific motoneuron pool exhibiting LTF (5, 6); 3) confirming that ventilatory LTF can be elicited in unanesthetized animals of multiple species (66); and 4) demonstrating that ventilatory LTF in unanesthetized animals is greater during sleep vs. wakefulness (71, 92). Since the initial descriptions of respiratory LTF in animal models, subsequent work has shown that LTF of ventilation can be evoked in humans during sleep (3, 78) and wakefulness (36, 62), although it may require mild background hypercapnia (61).

Work in animal models has generated considerable information concerning the cellular/molecular mechanisms of AIH-induced LTF (10, 66). These studies have identified multiple, distinct cellular cascades capable of giving rise to phrenic motor plasticity under different conditions (10). Most forms of AIH-induced LTF require serotonin receptor activation on or near respiratory motoneurons (6, 10, 29). Cellular mechanisms of phrenic motor facilitation (pMF) initiated by 5-HT2 (type A or B) receptor activation have been described as the Q pathway to pMF since these are Gq-protein coupled metabotropic receptors. Necessary downstream signaling includes activation of protein kinase C, de novo synthesis of brain-derived neurotrophic factor (BDNF) (5), activation of the high-affinity BDNF receptor tropomyosin-related kinase B (TrkB), and ERK MAP kinase signaling (43). The Q pathway also requires superoxide formation via NADPH oxidase (58, 59). The reactive oxygen species apparently inhibit okadaic-acid-sensitive serine/threonine phosphatases that normally constrain expression of phrenic LTF (60, 100, 102).

![Timeline depicting some of the important milestones in the study of intermittent hypoxia and respiratory neuroplasticity. Specific emphasis is placed on the initial seminal work that established the concept of “respiratory memories,” and then on publications that have directly lead to the use of intermittent hypoxia as a potential therapeutic modality in humans with spinal cord injury (SCI). This timeline represents a summary, and many important contributions were not included.](https://jap.physiology.org/doi/10.2203/33.1.on July 14, 2017)
A distinct pathway to pMF, referred to as the \( S \) pathway, is initiated by \( G_s \)-protein-coupled metabotropic adenosine \( (A_{2A}) \) (33) and/or 5-HT\(_7\) receptors (41). The \( S \) pathway involves necessary downstream signaling via cyclic AMP, de novo synthesis of an immature TrkB isoform (33), and Akt signaling. Importantly, the \( Q \) and \( S \) pathways do not summate to produce enhanced pMF; rather, their complex interactions are characterized by mutual “cross-talk inhibition” (14, 40, 76). For example, moderate protocols of AIH stimulate serotonin release and activation of high-affinity 5-HT\(_2\) receptors, which enables the \( Q \) pathway to dominate. In contrast, more severe AIH protocols result in activation of \( A_{2A} \) and 5-HT\(_7\) receptors, which blocks the \( Q \) pathway and thus enables the \( S \) pathway to drive pMF. Although the mechanisms of cross-talk inhibition from the \( Q \) to \( S \) pathway are unknown, protein kinase A mediates cross-talk inhibition from the \( S \) to the \( Q \) pathway (42). A summary of essential elements in the \( S \) and \( Q \) pathways to pMF is provided in Fig. 2.

**METAPLASTICITY AND INTERMITTENT HYPOXIA**

With repeated exposure to AIH (rAIH) it is essential to know if the effects accumulate, habituate, or remain unchanged. To be useful therapeutically, it is critical that repeated AIH presentations provide cumulative and continued impact in terms of both magnitude and duration of its beneficial effects. Cumulative effects can be considered “metaplasticity,” since the plasticity (i.e., LTF of phrenic motor output) itself exhibits plasticity (24, 67). Preclinical work in rat models has established that repeated intermittent hypoxia elicits phrenic LTF metaplasticity. For example, Ling et al. (56) first reported that pretreatment with chronic intermittent hypoxia (i.e., intermittent hypoxia exposures 8–12 h per day for 1 wk) enhances AIH-induced phrenic LTF. However, chronic intermittent hypoxia is too severe for clinical application; subsequent work focused on more modest rAIH protocols (73). Wilkerson and Mitchell (101) set the stage for future therapeutic applications of rAIH by showing that a paradigm of 10, 5-min episodes of 11% \( O_2 \) for 7 consecutive days evokes LTF metaplasticity without evidence for systemic hypertension (101). This rAIH paradigm also increased BDNF expression in the vicinity of phrenic motoneurons and enhanced the capacity for LTF.

**INTERMITTENT HYPOXIA AND SCI**

Since intermittent hypoxia elicits both respiratory motor plasticity and metaplasticity, several investigations have been performed to examine the therapeutic potential of AIH or rAIH to treat neurological conditions associated with impaired respiratory motor output (11, 12, 97). SCI represents one condition that can benefit from increased spinal synaptic transmission to respiratory motoneurons and/or associated neural networks (11, 65).

Axonal connections between the brain and spinal cord are at least partially interrupted by SCI, and the loss of motor, sensory, and autonomic function below the injury has devastating consequences. More than half of SCIs occur in the cervical region, impairing motor function and sensory feedback from the limbs. The majority of spinal injuries are incomplete, and some degree of spontaneous functional recovery does occur in the weeks to months after injury. Such spontaneous recovery is often attributed to plasticity in uninjured spinal pathways or other areas of the central nervous system (CNS). Unfortunately, spontaneous recovery of motor and/or sensory function is modest at best and seldom enables complete restoration of function. Thus a major focus of contemporary clinical and preclinical SCI research is aimed at enhancing CNS plasticity to enhance functional recovery. Although numerous therapeutic strategies have been investigated to enhance motor recovery after SCI, few have yielded robust outcomes when replicated or translated to clinical populations.

![Fig. 2. Working model of the cellular pathways contributing to long-lasting phrenic motor facilitation triggered by intermittent hypoxia. The highly simplified drawing depicts “respiratory drive” as a single axon terminal originating from the brainstem. Membrane proteins and intracellular pathways are depicted on a phrenic motoneuron. The \( Q \) pathway (left) is elicited by intermittent activation of \( G_s \)-coupled metabotropic receptors (e.g., 5-HT\(_2\) or \( \alpha \)), followed by activation of PKC, new synthesis of BDNF, activation of mature tropomyosin-related kinase B (TrkB), and activation of ERK MAP kinases (pERK). The \( S \) pathway (right) is elicited by \( G_q \)-coupled metabotropic receptors (e.g., 5-HT\(_7\) and \( A_{2A} \)), followed by activation of cAMP, new synthesis of an immature TrkB isoform, and downstream signaling via Akt phosphorylation/activation (pAkt). The specific mechanisms by which pERK (\( Q \) pathway) and pAkt (\( S \) pathway) elicit persistent increases in phrenic motoneuron output are not known but are likely to involve changes in motoneuron excitability and/or synaptic strength. pLTF, phrenic long-term facilitation.](#)
plasticity and restore motor function. Of equal importance, these strategies must be “translatable” to the clinic.

INTERMITTENT HYPOXIA AND SCI: PRECLINICAL RESPIRATORY STUDIES

The first study to explore the therapeutic potential of intermittent hypoxia for mitigating respiratory impairment after SCI was published in 2003 (31). In this study, rats were exposed to either chronic intermittent hypoxia [5-min hypoxic episodes (11% O2), 5-min normoxic intervals, 12 h per night, and 7 consecutive days] or a similar protocol of normoxia beginning 1 wk following C2 spinal hemisection (C2Hx). Increased spontaneous inspiratory phrenic burst amplitude was observed ipsilateral to C2Hx in hypoxia-treated rats. Furthermore, electrical stimulation of the contralateral spinal cord above the injury demonstrated increased strength of crossed-spinal synaptic pathways to phrenic motor neurons ipsilateral to the side of injury following hypoxia conditioning. The authors were careful to point out potential shortcomings that may limit or constrain the use of chronic intermittent hypoxia as a therapeutic tool; specifically, the potential for pathophysiological comorbidities made it unsuitable as a treatment. Subsequently, Golder and Mitchell (32) demonstrated that even a single presentation of AIH was sufficient to enhance respiratory motor output (i.e., phrenic LTF) below a C2Hx but only following chronic injury (8 but not 2 wk postinjury). Furthermore, the time dependence of AIH effects on phrenic LTF following C2Hx was strongly correlated with the initial loss and subsequent partial recovery of serotonergic innervation in the phrenic motor nucleus.

A subsequent study focused on daily AIH as a therapeutic approach [10, 5-min hypoxic episodes (11% O2), 5-min normoxic intervals, 7 consecutive days beginning 1 wk post-C2Hx injury] (57). Tested 1 day after the final AIH exposure (2 wk postinjury), daily AIH treated rats demonstrated: 1) substantial recovery of breathing capacity (unanaesthetized, spontaneously breathing); 2) increased spontaneous phrenic motor output ipsilateral to injury; 3) strengthened crossed-spinal synaptic pathways to phrenic motor neurons; and 4) increased BDNF, TrkB, and phospho-TrkB expression in and around phrenic motor neurons (57). These functional benefits were not associated with evidence of CNS pathology, such as hippocampal cell death and/or reactive gliosis. More recent studies investigating respiratory muscle EMG activity (72, 74) confirm this finding and indicate that both AIH and daily AIH act primarily on respiratory pathways not directly impacted by SCI; specifically, increased activity occurred predominantly in contralateral (intact) diaphragm and intercostal muscle EMG activity 7 days postinjury. In a study by Navarrete-Opazo et al. (74) rats were exposed to daily AIH [10, 5-min hypoxic episodes (11% O2), 5-min normoxic intervals, 7 consecutive days beginning 1 wk post-C2Hx injury] followed by weekly presentations of AIH for an additional 8 wk. The functional respiratory benefits of daily AIH persisted at least 1 wk after completion of daily AIH exposures and were shown to be mediated by an adenosine (not serotonin)-dependent mechanism (74). Interestingly, the subsequent weekly “reminder” presentations of AIH were not sufficient to maintain these effects, raising the possibility that more frequent rAIH is necessary to prolong the observed effects. Collectively, these studies suggest that rAIH will be an effective therapeutic for restoring breathing capacity in patients with SCI. Furthermore, these studies represent an important step in the clinical translation of rAIH to clinical populations since the daily AIH protocol confers functional benefits without attendant pathology (57, 87).

INTERMITTENT HYPOXIA AND SCI-NONRESPIRATORY MOTOR SYSTEMS

The response to hypoxia is not restricted to respiratory neurons/networks. There is abundant literature suggesting that hypoxia activates raphe serotonergic neurons, and that serotonin is subsequently released in diverse regions of the brainstem and spinal cord (49, 66). Examples are as follows: 1) carotid chemosensitive neuron activation (68) increases caudal raphe neuron activity; 2) hypoxia increases c-fos labeling in caudal raphe serotonergic neurons, consistent with increased activity (21, 22); and 3) hypoxia releases serotonin in the brainstem of anesthetized cats (83) and the spinal cord of anesthetized rats (49). Since raphe-spinal serotonergic neurons project throughout the spinal cord, including nonrespiratory regions, and most motoneurons express serotonin receptors (39), it is not unlikely that the same AIH-induced, serotonin-dependent mechanisms of spinal motor plasticity are manifest in nonrespiratory motor systems. In fact, there is accumulating evidence that AIH-induced neuroplasticity is not limited to the neural system controlling breathing, and can also occur in other motor systems (Fig. 3).

Lovett-Barr et al. (57) were the first to systematically investigate the impact of rAIH in nonrespiratory motor systems after SCI. One month after cervical SCI in rats, rAIH for 7 consecutive days improved skilled forelimb function in a horizontal ladder-walking task. These functional benefits lasted at least 3 weeks after treatment and were not associated with any evi-

Fig. 3. Intermittent hypoxia can act throughout the spinal neuraxis following SCI. Initial work on acute intermittent hypoxia (AIH) focused on the respiratory system, but recent work (see Fig. 1) demonstrates that upper and lower extremity motor function is also enhanced after daily AIH. This conceptual diagram depicts strengthening of synaptic connections in the mid-cervical (phrenic-diaphragm motor system), low cervical (forelimb/upper extremities), and lumbo-sacral spinal cord (leg/ankle function). We propose that common mechanisms contribute to plasticity in these respiratory and nonrespiratory motor systems after AIH therapy (e.g., triggered by serotonin receptor activation; see Fig. 2 for a more comprehensive summary). Collectively, evidence from both human and animal models indicates that AIH is safe and easy to administer, induces robust spinal neuroplasticity, and may be an effective therapeutic approach to enhance motor function in persons with chronic SCI.
Interruption of cervical or thoracic SCI was exposed to rAIH effects on respiratory function in a clinical population. In a follow-up study, Prosser-Loose et al. (81) demonstrated that pairing AIH (11% O₂; 10, 5-min episodes per day × 7 days) with task-specific training was necessary for observed functional benefits. Rats exposed to daily AIH (7 days) beginning 4 wk post-SCI exhibited the most robust functional recovery when AIH was paired with ladder-walking practice vs. treadmill training or AIH alone. These functional improvements were retained up to 8 wk posttreatment and were not found in nontrained motor behaviors, such as reach to grasp, grip strength, and paw use preference. These results confirm the effectiveness of repeated AIH as a therapeutic approach to restore motor function but demonstrate that rehabilitation is optimal with combined AIH + task-specific training, at least in nonrespiratory motor systems.

TRANSLATION TO CLINICAL POPULATIONS

The first report that AIH could be safely implemented in a clinical SCI population was published in 2012 (96). Trumbower et al. showed that AIH could modulate somatic motor function in humans by demonstrating that a single AIH presentation increased ankle plantar flexor strength in 13 humans with chronic (~15 yr postinjury) incomplete SCI. Specifically, changes in maximal voluntary isometric ankle plantar flexor torque and plantar flexor EMG activity were assessed before and after AIH (15, 1-min hypoxic exposures: 9% O₂, SαO₂ ~80%; 1-min intervals). With the use of a double blinded, cross-over design, results were compared between AIH and sham normoxia (e.g., room air: 21% O₂). Immediately following AIH, plantar flexion torque increased 82% above baseline, and increased strength continued for more than 90 min post-AIH. Improved muscle strength remained elevated for more than 4 h in several of the study participants, suggesting the potential for long-lasting effects. Increased ankle plantar flexor EMG activity correlated with increased torque. No differences in plantar flexion strength or EMG activity were observed in sham experiments.

A recent study by Tester et al. (93) was the first to assess rAIH effects on respiratory function in a clinical population. Humans with chronic cervical or thoracic SCI were exposed to 8, 2-min intervals of 8% inspired O₂ for 10 consecutive days. Significant and sustained increases in minute ventilation (i.e., ventilatory LTF) were observed on each day of AIH exposure. However, LTF magnitude was constant across the 10-day period; cumulative responses were not detected. This study provided proof-of-principle that AIH could be used to enhance breathing function in individuals with chronic SCI, laying a foundation for future studies concerning appropriate intermittent hypoxia protocols for humans.

Collectively, initial AIH studies in humans with chronic SCI are promising; no adverse events have been reported in the initial trials (48, 93, 96).

COMBINATORIAL THERAPIES

AIH may serve as a “stand alone” therapy or may be more effective when paired with other rehabilitation (task-specific) approaches (Fig. 3). For example, the finding that AIH increases ankle strength may be important clinically, as reduced ankle strength is a major factor affecting mobility after SCI (96). Plantar flexor muscle activation contributes significantly to the energetics of normal walking; thus pairing AIH with traditional plantar flexor strength training might further enhance recovery. AIH may also have utility in the context of newer (still experimental) interventions, such as cell transplantation (53). In the next section, we review three substantially different approaches to spinal cord rehabilitation that have a common thread: each has potential to benefit if paired appropriate AIH “priming.” Specific examples include 1) locomotor training (i.e., traditional “activity-based” physical therapy); 2) electrical stimulation of the spinal cord; and 3) cell transplantation (e.g., stem/progenitor cell therapy).

PAIRED AIH AND TASK-SPECIFIC REHABILITATION/TRAINING

Hayes et al. (38) tested the hypotheses that 1) daily AIH (5 days) augments locomotor function (e.g., walking speed and endurance) in patients with chronic, incomplete SCI; and 2) combined daily AIH with walking practice enhances the functional benefits of AIH alone. In their study, 19 individuals with incomplete SCI received AIH (15 × 90-s hypoxic episodes of 9% O₂; 60-s normoxic intervals) or daily sham normoxia exposures. AIH was given alone or combined with 30 min of overground walking practice 1 h later. Daily AIH improved both walking speed (10-m walk test) and endurance (6-min walk test). Combined daily AIH and walking practice resulted in greater improvements in walking endurance than daily AIH treatment alone. These benefits persisted up to 1 wk posttraining, but by 2 wk, walking endurance was not different from daily AIH alone. Participants were monitored for negative side effects during AIH exposures, including assessment of headaches, pain, lightheadedness, dizziness, altered vision, respiratory distress, cyanosis, spasticity, autonomic dysreflexia, cardiopulmonary/circulatory instability, or changes in motor or sensory function. The rAIH paradigm was well tolerated by all study participants, and no adverse events were observed or reported during or following the study.

One of the most intriguing findings of the study of Hayes et al. relates to the magnitude of the effects given the limited treatment duration. Contemporary therapies for individuals with SCI typically consist of several weeks or months of intensive training; however, clinically meaningful improvements are often limited. Indeed, when compared with a recent study that examined the effects of 60 sessions (12 wk) of different locomotor therapies, the effect sizes for walking speed and endurance following AIH and AIH + walking were more than twice those achieved by traditional locomotor therapies. Furthermore, AIH and AIH + walking resulted in walking speeds and walking endurance that were comparable to or greater than those seen in training studies of much longer durations. Indeed, more than 30% of subjects that received AIH + walking practice achieved a clinically meaningful change in walking speed and more than 70% achieved a clinically meaningful change in walking endurance (38).
SPINAL CORD ELECTRICAL STIMULATION AND AIH

Tonic spinal cord stimulation has recently garnered a great deal of attention as a powerful tool to restore lost function following SCI. Although the underlying mechanisms are not yet clear, applying electrical currents to the injured spinal cord can induce profound functional benefits. For example, electrical stimulation of the ventral surface of the thoracic spinal cord triggers rhythmic diaphragm contractions after complete transection of the high cervical spinal cord in dogs and rats (16–18, 50). Furthermore, epidural stimulation of the lumbar spinal cord in humans with SCI restores voluntary activation of distal muscles, even in patients with severe SCI (2, 35). In animal models, the efficacy of spinal cord stimulation is enhanced by pharmacologic interventions that activate monoamine receptors. For example, serotonin receptor agonists produce rhythmic stepping when coupled with spinal stimulation in rats (69, 70). Since rAIH enhances spinal synaptic efficacy (27, 57) and increases spinal serotonin terminal density and receptor expression (87), AIH may be a modality that can increase the efficacy of electrical spinal stimulation paradigms.

CELLULAR THERAPIES

The goals of tissue transplantation after SCI include filling and/or “bridging” cyst cavities, replacing lost cells (e.g., motoneurons, interneurons, and oligodendrocytes), and creating a favorable environment for growth (82). Fundamental to the therapeutic success of cell transplantation is the optimization of cell yield, generation of neuronal phenotypes, and enhancement of graft survival and graft-host connectivity posttransplantation. To date, very little progress has been made toward enhancing host-graft functional integration with preconditioning and/or training paradigms. Studies using “enriched environments” (e.g., larger cage, toys, running wheels, etc.) in association with cell transplants have demonstrated improved functional outcomes of cell transplantation following SCI (25). Furthermore, these studies suggest that therapies altering the “trophic environment” may enhance host-graft integration.

Our group and others have explored the use of fetal spinal cord (FSC) transplants to reconstruct disrupted spinal circuitries (i.e., “gray matter repair”) and/or to create novel neuronal relays (reviewed in Ref. 82). FSC grafts represent transplants of lineage-restricted precursors (i.e., cells with a predetermined fate, e.g., interneurons) and residual stem cell populations (9, 54, 55, 94, 95). FSC grafts typically fill spinal lesion cavities by 1 mo posttransplantation (95), become anatomically integrated with host-spinal interneurons (52), and are associated with improved locomotion after SCI (reviewed in Ref. 82). We recently found that neurons within mature FSC transplants in the C2 spinal cord respond to hypoxia with increased bursting (52). Since FSC graft neurons respond to hypoxia (52), and host neurons in the immediate vicinity of a cervical graft (e.g., phrenic motoneurons, interneurons) also robustly increase discharge during hypoxia (86), we reasoned that rAIH may be a stimulus that could enhance the modest synaptic connectivity that appears to develop between the host respiratory circuitry and FSC graft neurons following cervical transplantation (52, 99). In a preliminary study, we therefore explored the impact of rAIH on neuronal discharge in mature FSC grafts in the cervical spinal cord (53). With the use of previously published methods (52), adult male rats with C2Hx received FSC transplants (embryonic day 14 tissue (82)) at the time of injury. Beginning 1 or 6 wk after the FSC transplant procedure, a paradigm of rAIH was initiated (10, 5-min episodes of 10% inspired O2, 3 days per wk). At 10 wk postinjury, electrical activities of graft neurons and the ipsilateral phrenic nerve were recorded in anesthetized, vagotomized, and ventilated rats using published methods (52). Synchronized bursting of FSC graft neuron activity (i.e., “population activity”) was observed in 7 out of 12 (58%) of transplanted animals that received hypoxia training. We have never observed this response in control (i.e., non-rAIH exposed) FSC grafts (52). Moreover, we found two very clear examples of FSC grafts that displayed respiratory-related discharge patterns during baseline or hypoxia (see Fig. 4). During these recordings, we repeatedly removed the recording electrode from the visibly discernable graft tissue (see examples in Refs. 52, 99) and then reinseted the electrode to confirm the observation. In prior experiments, we have never observed respiratory-related neuronal discharge in control (nonhypoxia treated) FSC grafts in the cervical spinal cord (52). Further work is obviously needed to validate these initial observations and to determine the functional significance of respiratory-related discharge in graft neurons. Nevertheless, these data suggest that rAIH exposure may provide a tool to enhance the “functional integration” of neuronal progenitor transplants with host respiratory neurons.

Another potential use of AIH in the context of cellular transplantation is to “precondition” cells before transplantation. For instance, culture of neural progenitor cells in a low O2 environment increases cell proliferation and yield (90), makes cells less susceptible to programmed cell death (90), and elaborates neuronal differentiation (8). Moreover, in vivo AIH exposure before harvest of subventricular zone-derived (SVZ) neural progenitor cells results in an increase their subsequent in vitro expansion (84). In that study, rAIH increased Pax6 expression (a transcription factor involved in neuronal fate determination) in the harvested SVZ cells and was associated with increased neuronal differentiation. Thus in vivo rAIH can enhance the viability of subsequent in vitro SVZ-derived cell cultures and may provide a means to “prime” neural progenitor cells prior to transplantation into the injured CNS.

OPTIMIZATION OF rAIH PROTOCOLS

To realize the potential of rAIH for clinical use, it is necessary to determine optimal protocols including the number, frequency, and severity of hypoxic episodes in patients (97). It will be of fundamental importance to minimize or eliminate potentially adverse consequences of rAIH such as hypertension, autonomic dysreflexia, neuroinflammation, reactive gliosis, and hippocampal cell death (34, 79, 80, 85, 105). Whereas severe intermittent hypoxia (as in obstructive sleep apnea) causes severe morbidity, low-moderate doses of rAIH do not appear to induce pathology (73). It is not yet possible to definitively state the appropriate (or “best practice”) rAIH paradigm, but some clear guidelines are emerging (see Ref. 73). Paradigms using inspired O2 in the range of ~9–16% and with relatively low numbers of exposures (e.g., 3–15 episodes) have predominantly beneficial effects, whereas more severe protocols (e.g. inspired O2 <9%) and more episodes per day (>50) produce dose-dependent pathology. It is possible that variations in the number exposures or the duration of exposures or treatments may yield even greater therapeutic benefit in
humans. Future studies are warranted to maximize rAIH-induced functional gains and sustainability without invoking maladaptive plasticity and adverse consequences.

ADDITIONAL CONSIDERATIONS REGARDING AIH AS A THERAPEUTIC MODALITY

Multiple factors may undermine (or enhance) AIH-induced plasticity and, therefore influence the therapeutic efficacy of rAIH. We will briefly comment on a few variables that merit particular consideration.

Inflammation. Systemic inflammation persists for months and even years after SCI and can have considerable impact on the degree of motor recovery (1, 88). The impact of inflammation on neurons and networks that regulate breathing has only recently been appreciated (15, 98). Initial explorations of this topic indicate that even low-grade systemic inflammation dramatically impairs the ability to express AIH-induced respiratory plasticity (46, 47). Thus AIH-induced LTF of phrenic motor output is abolished by the modest inflammation caused by low-dose systemic lipopolysaccharide (46, 98) or a “high dose” of intermittent hypoxia [e.g., repeated intermittent hypoxia exposures throughout a 24 h period (45)]. In both cases, phrenic LTF can be restored by a nonsteroidal anti-inflammatory drug (ketoprophen), which is thought to act either via inhibition of COX1/2 enzymatic activity or via inhibition of the proinflammatory transcription factor NF-κB (47).

In addition to spontaneous, ongoing systemic inflammation associated with SCI, individuals with SCI are highly susceptible to acute inflammation associated with, for example, bladder infections or skin lesions. Unfortunately, at this point little is known concerning how ongoing or acute systemic or neural inflammation influence spontaneous functional recovery of breathing capacity following SCI or how it impacts the therapeutic efficacy of rAIH. It may be that anti-inflammatory treatments increase the efficacy of rAIH therapy.

Sleep-disordered breathing. SCI is associated with a considerable increase in the prevalence of sleep-disordered breathing, including both central and obstructive sleep apnea (OSA) (23). This may be an important consideration since AIH-induced ventilatory LTF is enhanced in neurologically intact individuals with OSA (30, 51, 91). One theory is that intermittent hypoxia associated with chronic OSA triggers metaplasia in phrenic LTF (56) and ventilatory LTF (63). One prior study with a small sample size failed to detect any difference in the ventilatory LTF following AIH in individuals with SCI, with or without comorbid OSA (93). From a different perspective, a single night of central or obstructive OSA may trigger neuroinflammation that is qualitatively different from that experience after chronic intermittent hypoxia or OSA, and this short-term effect serves to undermine AIH-induced phrenic LTF (45). The topic of sleep-disordered breathing in individuals with SCI is complex (28), and we suggest that the past

Fig. 4. Anecdotal data suggest that rAIH can “train” a spinal cord transplant following cervical SCI. In this experiment, rat embryonic day 14 fetal spinal cord tissue was transplanted into acute C2 hemileision (C2Hx) cavity in adult rats. Rats were then exposed to 10, 5-min hypoxic episodes (10% O₂, balance N₂) for 10 wk, beginning 1 wk post-C2Hx. After 10 wk, electrical activity of graft tissue and the ipsilateral phrenic nerve were recorded in anesthetized, vagotomized and ventilated rats during baseline (FIO₂ = 0.5–0.6) and hypoxia (FIO₂ = 0.13–0.15). The graft tissue was visualized using a dorsal surgical approach, and a 0.4–0.8 M electrolyte (carbonate-3; Kation Scientific) was inserted directly into the graft. A: examples of graft and phrenic nerve activity (both “raw” and “integrated”, f) during baseline conditions and hypoxic challenge. The graft recording shows considerable tonic activity, but a clear respiratory-related discharge can be appreciated. B: cross-correlation analysis of the graft and phrenic bursting depicted in A. The correlogram shows a clear central peak that is consistent with the hypothesis that the graft and host phrenic motor neuron pool shared a common synaptic input. C: waveform averages (several minutes of data) of graft and phrenic signals. The averages were generated using phrenic burst onset as a trigger (arrows). Graft neurons exhibit inspiratory activity during baseline and hypoxia-triggered preinspiratory activity in the graft recording. Note also that tonic activity increased during hypoxia in the graft but decreased in the host phrenic activity.
Drug therapies. Concomitant use of certain drugs may alter the impact of rAIH on spinal neuroplasticity. Drugs that reduce spasticity, such as baclofen, activate inhibitory neurotransmitter receptors on spinal neurons (13), potentially reducing the excitability of spinal motoneurons and undermining the therapeutic efficacy of rAIH. In contrast, pharmacological inactivation of A2A receptors (40, 75) or alterations in serotonin receptor activity may enhance or undermine the therapeutic efficacy of rAIH in restoring motor function. For example, caffeine is an A2A receptor antagonist and may be highly beneficial in amplifying the impact of rAIH therapy in individuals with chronic SCI.

Many individuals with chronic SCI take antidepressants, such as selective serotonin reuptake inhibitors (SSRIs) or monoamine oxidase inhibitors. These types of drugs elicit complex effects on serotonergic function, increasing serotonin availability in the extracellular space, yet downregulating key serotonin receptor subtypes (e.g., 5-HT2A) with chronic administration. Because serotonin elevations are sustained and key receptor subtypes decrease their expression with chronic SSRI administration, their impact on rAIH-induced functional recovery is uncertain.

Gender. Consideration of sex-related differences in response to rAIH is important, as sex hormones greatly influence the magnitude of AIH induced phrenic and hypoglossal LTF. Specifically, LTF is absent in male rats after gonadectomy but restored with testosterone replacement (104). Furthermore, the phase of the estrus cycle and levels of progesterone in females influences the magnitude of LTF and ventilatory responses (103). After SCI, low testosterone is common in males (19), and altered menstrual cycles are common in females (89). Both of these effects may influence the extent to which individuals respond to rAIH therapy. The study by Tester et al. (93) investigating daily AIH in subjects with chronic SCI provides suggestive evidence that sex/sex hormones may indeed be an important consideration for the therapeutic efficacy of rAIH. In their study, repeated AIH appeared to enhance ventilatory LTF in males and to actually reduce this response in females. However, heterogeneity of injury and the limited sample size (n = 8) in this study precluded the authors from making firm conclusions concerning the impact of sex differences on the magnitude of LTF; further studies in a larger population of individuals with SCI are warranted.

Level, severity, and chronicity of injury. The neurological level of SCI is always an important consideration for neurorehabilitation strategies. In regards to breathing, cervical vs. thoracic spinal cord injuries are likely to have different effects on inspiratory (diaphragm/intercostal) vs. expiratory (intercostal/abdominal) motor function. In the study by Tester et al. (93), two individuals with thoracic SCI showed no AIH-induced improvements in ventilatory outcomes, whereas the majority of cervically injured participants showed improvements in forced vital capacity (FVC) and forced expiratory volume in 1 s (FEV1). Accordingly, rAIH may be more beneficial to individuals with cervical vs. thoracic injuries since they have greater deficits in inspiratory function. The severity of the SCI is also an important consideration, as severe disruption of descending neural pathways may limit the potential substrate for intermittent hypoxia-induced plasticity. Lastly, the chronicity of injury is known to influence the extent of neuroplasticity and therapy-induced functional gains in persons with SCI (44). The fact that improvements in both respiratory and nonrespiratory motor function were observed in all three human trials of AIH is promising, as these trials were conducted in individuals with chronic injuries, suggesting that this therapy has the potential to elicit functional improvements long after the onset of injury.

Interactions between the molecular pathways that trigger respiratory plasticity. There is “cross-talk inhibition” between pathways to long-lasting phrenic motor facilitation, and these interactions may influence the degree of functional recovery induced by rAIH (14). For example, during severe AIH, greater adenosine formation/accumulation increases A2A receptor activation, resulting in dominant S pathway activation (76) with subsequent Q pathway suppression. Conversely, moderate AIH stimulates serotonin release with coincident adenosine accumulation, leading to predominant Q pathway activation (6, 29). The interactions between pathways enable either pathway to predominate depending on condition; however, it is also possible for them to reach a balance where they offset one another, effectively canceling the functional benefits of AIH. Accordingly, one possibility to consider is that at certain times post-SCI, or with certain rAIH protocols, these inhibitory interactions could compete, creating an impasse where neither the S nor the Q pathways will be expressed as motor facilitation. In this circumstance, the potential benefits of rAIH therapy would be undermined.

CONCLUSION

Recent trends in SCI rehabilitation highlight the benefits of utilizing combinatorial approaches to amplify small improvements of single interventions. The combination of traditional rehabilitation approaches with therapies designed promote neuroplasticity or regeneration (e.g., cellular transplantation, gene therapy, etc.) has had some success in animal models, but translation to humans has been challenging. rAIH is a very attractive approach in this regard since it can noninvasively induce spinal plasticity and has had remarkable functional impact in animal models of SCI and in a limited number of human studies. Initial observations suggest that AIH can be effectively paired with traditional rehabilitation paradigms (e.g., locomotor training) and with more experimental approaches such as cell transplantation (Fig. 4).

One of the most important barriers to overcome is to change the attitudes of clinicians and patients regarding the potential therapeutic benefits of breathing low levels of O2. Recent trials in humans with SCI will help in this regard, as they demonstrate that rAIH can be safely administered to humans with chronic, incomplete SCI without negative consequences. To translate rAIH to clinical and/or at home use as a therapeutic tool, design of suitable devices and Food and Drug Administration approval are essential. Salient features to consider in the design of the device include safety, cost (initial purchase as well as the cost of daily use/maintenance), size, personnel requirements for operation, and ease of setup and use.

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