

Treatments for traumatic brain injury with emphasis on transcranial near-infrared laser phototherapy

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Abstract: Traumatic brain injury (TBI) is a growing health concern affecting civilians and military personnel. In this review, treatments for the chronic TBI patient are discussed, including pharmaceuticals, nutraceuticals, cognitive therapy, and hyperbaric oxygen therapy. All available literature suggests a marginal benefit with prolonged treatment courses. An emerging modality of treatment is near-infrared (NIR) light, which has benefit in animal models of stroke, spinal cord injury, optic nerve injury, and TBI, and in human trials for stroke and TBI. The extant literature is confounded by variable degrees of efficacy and a bewildering array of treatment parameters. Some data indicate that diodes emitting low-level NIR energy often have failed to demonstrate therapeutic efficacy, perhaps due to failing to deliver sufficient radiant energy to the necessary depth. As part of this review, we present a retrospective case series using high-power NIR laser phototherapy with a Class IV laser to treat TBI. We demonstrate greater clinical efficacy with higher fluence, in contrast to the bimodal model of efficacy previously proposed. In ten patients with chronic TBI (average time since injury 9.3 years) given ten treatments over the course of 2 months using a high-power NIR laser (13.2 W/0.89 cm² at 810 nm or 9 W/0.89 cm² at 810 nm and 980 nm), symptoms of headache, sleep disturbance, cognition, mood dysregulation, anxiety, and irritability improved. Symptoms were monitored by depression scales and a novel patient diary system specifically designed for this study. NIR light in the power range of 10–15 W at 810 nm and 980 nm can safely and effectively treat chronic symptoms of TBI. The clinical benefit and effects of infrared phototherapy on mitochondrial function and secondary molecular events are discussed in the context of adequate radiant energy penetration.

Keywords: infrared, traumatic brain injury, TBI, transcranial infrared light therapy, transcranial laser therapy

Introduction

Traumatic brain injury (TBI) has recently moved into the limelight due to the recognition of its impact on professional athletes and military personnel. Yet, TBI is neither a new problem nor limited to those two populations. The Centers for Disease Control and Prevention estimated that 1.5 million Americans sustained TBI annually in 2000.¹ As of 2006, the estimates had risen to 1.7 million brain injuries annually.^{2,3} Undoubtedly, these point prevalence proportions will increase as military personnel return home,⁴ and the problem of repeated mild TBI (mTBI) becomes more recognized in sports.⁵ Current estimates of the prevalence of TBI among veterans range from 9.6%⁶ to 20%,⁷ with an estimated total of more than 300,000 cases of TBI among military personnel since 2000.⁴ The current estimates of the combined number of sports-related concussions and brain injuries in the US are 1.6–3.8 million annually.^{8–10}

TBI results in a wide spectrum of neurological, psychiatric, cognitive, and emotional consequences. In part, the variation is related to the severity of the injury (mild, moderate, severe TBI), which is stratified based on Glasgow Coma score, periods of unconsciousness, and degrees of amnesia. Furthermore, the diversity of sequelae can be related to the areas of the brain that are injured, the severity of the injury (highly variable within the classification of “mild” and “moderate”), and the evolution of the injury over time due to neuroinflammatory processes.^{11,12} Additional mechanisms thought to underlie the damage of TBI include decreased mitochondrial function, calcium and magnesium dysregulation, excitotoxicity, disruption of neural networks, free radical-induced damage, excessive nitric oxide, ischemia, and damage to the blood–brain barrier. Together, these can contribute to a progression of the damage over time.

Patients with TBI can experience headache, visual disturbances, dizziness, cognitive impairment, loss of executive skills, memory impairment, fatigue, impulsivity, impaired judgment, emotional outbursts, anxiety, and depression.^{3,13–23} The situation can be further clouded by secondary and/or comorbid posttraumatic stress disorder (PTSD), depression, and anxiety,^{17–25} which can have symptoms that overlap with those described above and appear to be increasingly likely with repetitive concussive or subconcussive brain injury.^{5,24,26}

Treatments for TBI

Pharmacological treatments

Pharmacological treatment largely targets the neuropsychiatric sequelae of TBI, rather than providing any means of healing or repairing injury. In general, pharmacological treatment is focused on the modulation of major neurotransmitter systems – dopaminergic, serotonergic, noradrenergic, acetylcholinergic, and glutaminergic.²⁰ Disruption of the major neurotransmitter pathways may result from direct injury or excitotoxicity and other cytotoxic mechanisms.

The treatment of depression secondary to TBI is often approached with serotonin reuptake inhibitors. Several studies have examined the benefit of sertraline in post-TBI depression.^{27–29} Other serotonin reuptake inhibitors also have been examined. Tricyclic antidepressants appear to have some use in the treatment of post-TBI depression, although cautious dose titration is required. Patients with TBI are at greater vulnerability to sedation and cholinergic side effects of confusion and memory impairment. With serotonergic agents other than sertraline, cognitive effects also have been reported.³⁰ Similarly, lithium may be a less desirable agent in this population due to sedation and cognitive impairment.

Patients with TBI may respond at lower doses and lower blood levels than expected.

Modulation of the dopaminergic system may improve alertness, attention, and cognitive processing speed. The stimulants are most commonly used for this purpose. Methylphenidate facilitates the release of dopamine and slows its reuptake. Dextroamphetamine strongly inhibits reuptake of dopamine, slows down the breakdown of dopamine by monoamine oxidase, and somewhat increases the release of dopamine. These subtle differences are sometimes imperceptible to the patient, but at other times, a patient will do best on one or the other stimulant. Increasing dopamine in the reticular activating system leads to enhanced arousal. Increasing dopamine within the frontal cortex and the striatum leads to enhanced processing speed and attention. Some evidence suggests that the stimulants may enhance neuronal recovery after injury.^{31–33} There are numerous potential side effects with stimulants, including abnormal heart rhythms, decreased seizure threshold, and death, but these severe side effects are extremely rare. The most common side effects with stimulants are decreased appetite, stomach upset, and headache. These are most severe at the beginning of treatment and improve over time for most patients. Insomnia is another common side effect, which may be more frequent in those with a TBI. Amantadine and bromocriptine may also increase dopamine. Studies of these agents have shown reduced abulia, anergia, and anhedonia in those with TBI.^{34,35} Amantadine may cause confusion, hallucinations, and hypotension. Small studies have suggested some benefits of bromocriptine in cognitive function.^{36,37}

Arousal-enhancing agents also have found a use in the treatment of the neurocognitive sequelae of TBI. Modafinil is the oldest form of these medications, and armodafinil is an isomer of modafinil with longer activity and less side effects. These medications help to increase alertness and wakefulness. The precise mechanism of action of modafinil is unclear. It appears to increase histamine in parts of the brain involved in controlling the sleep–wake cycle; however, knock-out mice that lack histamine receptors still show increased wakefulness with modafinil.^{38,39} The picture is also murky for modafinil’s effect on orexins, which are wakefulness molecules in the hypothalamus.⁴⁰ Modafinil has been shown to weakly bind to the dopamine transporter – like the stimulants,⁴¹ and dopamine transporter knock-out mice show no response to modafinil.⁴² A number of research studies have examined the benefit of these agents in fatigue associated with multiple sclerosis, TBI, cancer, and other conditions.

Cognitive and memory impairments after TBI may reflect disruption of cholinergic function. The impact of anticholinergic agents on cognitive function of those with TBI supports this contention. Donepezil is the safest and most widely used of the cholinesterase inhibitors. Several reasonably large studies have shown improved memory and cognitive function.^{43–45} Donepezil has benefits in memory and cognition even several years after injury.^{45,46}

Anticonvulsants are often prescribed initially after a TBI due to heightened risk for seizures. Post-TBI mania or mood lability may respond well to anticonvulsants, such as carbamazepine or sodium valproate. They are also often used to treat aggression after TBI. The anticonvulsant agent, topiramate, has been shown to adversely affect cognitive function in the TBI patients.⁴⁷

While insomnia is a significant issue for patients with TBI, affecting between 15% and 84% (mean of 40%),^{3,13,19,21,23,48,49} little has been published on the treatment of this aspect of TBI. Benzodiazepines may be effective but carry a risk of disinhibition. Kemp et al⁴⁸ found that commonly used sleep aid, melatonin, was not effective. Antidepressants, including serotonin reuptake inhibitors and tricyclic antidepressants, are not effective in resolving insomnia in this population.⁴⁹ No single agent has emerged as a good solution for this symptom.

Cognitive rehabilitation

Cognitive rehabilitation now takes many forms and is often individualized to the particular needs of the patients. Protocols have been devised to remediate cognitive difficulties often encountered in those with TBI, such as impaired concentration, executive dysfunction, inattention, visual disturbances, memory dysfunction, and impaired language function. They range from simple strategies (using a planner to aid memory and organization) to specific protocols targeting particular cognitive functions (eg, short-term memory) that can be monitored with sequential neuropsychological testing. These interventions have been extensively reviewed elsewhere.^{50,51} Comprehensive programs which include psychotherapy and social skills components have been shown to have greater efficacy.^{50,52,53} Overall, reports of benefits have been mixed.^{54,55}

Behavioral therapies

Behavioral remediation strategies to eliminate problematic behaviors following TBI have met with mixed success, most often in terms of the poor generalization of specific skills to the outside world. Behavioral deficits that create difficulties for those with TBI and their families include poor hygiene, decline in tidying/cleaning habits, social withdrawal, reduced

social comprehension, impaired memory, and poor organization. Behavioral excesses that create difficulties for those with TBI and their families include aggression, sleep disruption, and perseverations. These have been reviewed elsewhere.⁵⁶

Nutritional supplements

Nutritional supplements, herbs, and nootropics have been utilized for many years and are increasingly popular among the patient populations. There remains little clinical research on many of these agents, perhaps reflecting a lack of funding more than a lack of efficacy. Acetyl-L-carnitine is an ester of L-carnitine and is thought to protect brain cells after injury when glucose metabolic pathways are compromised. During this period, acetyl-L-carnitine supports alternative ketogenic pathways for metabolism.⁵⁷ It is also believed to enhance cholinergic function. While there are several clinical studies on patients with Alzheimer's disease and preclinical data on animal models of TBI, the clinical literature on TBI remains sparse. Ginkgo biloba is a natural product of the tree by the same name. It has been shown to improve membrane fluidity and increase resistance to free-radical damage. It provides some subtle benefits to cognitive function in clinical studies of stroke, dementia, aging, and hypoxia damage.⁵⁸ It has not been systematically studied in TBI but is used extensively in clinic, often in combination with meclizine which is an avid scavenger of free radicals.⁵⁹ S-Adenosylmethionine (SAME) is a nutritional supplement which improves cell membrane fluidity and promotes the production of glutathione, an antioxidant. The benefit of SAME has been assessed in a single clinical study of TBI.⁶⁰ Patients receiving SAME had a 77% improvement in clinical scores of post-concussive symptoms. Citicholine provides a source of choline which can cross the blood-brain barrier. It has been used extensively in Europe and Japan as a treatment for TBI, stroke, and dementia. However, two large US studies failed to demonstrate significant benefit.^{61,62}

Piracetam and the related oxiracetam and phenylpiracetam have shown some promise as nootropic agents. In one double-blind, placebo-controlled study, piracetam improved several symptoms of post-concussive syndrome, including headache and vertigo.⁶³ More recent clinical studies have shown marginal benefit.⁶⁴ Huperzine-A, an extract of Japanese club moss, is a natural acetylcholinesterase inhibitor. It may serve as a natural alternative to donepezil, rivastigmine, or galantamine. Galantamine warrants special mention as it appears to also modulate nicotinic receptors and appears to have more persistent benefit in the treatment of Alzheimer's disease. It appears to modulate neuroimmune responses,

in addition to its effects on acetylcholinesterase.⁶⁵ Cerebrolysin is a polypeptide that purportedly mimics the actions of neurotrophic factors.^{66,67} Studies have shown that it can reduce beta amyloid and phosphorylated tau protein accumulation. It may promote neurogenesis, synapse formation, and functional recovery.⁶⁶ In animal models of acute TBI, cerebrolysin-treated rats had more surviving neurons in the area of impact and showed greater functional recovery.⁶⁷ In a clinical trial of acute TBI, patients were recruited within 24 hours of injury and treated for 3 months with daily intravenous infusion of cerebrolysin. At 3 months, those receiving cerebrolysin performed significantly better on the Cognitive Abilities Screening Instrument.⁶⁸ It remains unclear if cerebrolysin provides long-term nootropic benefit.

The elevation of free radicals in TBI suggests that antioxidants should be beneficial. Clinical trials of pharmacological antioxidants over the past 30 years have not yielded a useful agent in acute TBI.⁶⁹ Agents, such as tirilazad⁷⁰ and polyethylene glycol-conjugated superoxide dismutase, have failed to show benefit in acute TBI. Omega-3 fatty acids may enhance brain repair and recovery, based on animal and clinical studies.⁷¹ Similarly, vitamin D may offer neuroprotective and restorative benefits⁷² in the acute TBI setting. In chronic TBI, vitamin D and omega-3 fatty acids may work synergistically, as they both may reduce neuroinflammation, apoptosis, and oxidative stress.⁷³ Other nutritional supplements have been recommended, but prolonged therapy is necessary to possibly see benefits in TBI. A 6-month trial of ginkgo, vinpocetine, acetyl-L-carnitine, huperzine, alpha-lipoic acid, *n*-acetyl-cysteine, multivitamins, and over 5 g of omega-3 fatty acids daily yielded improved performance in cognitive testing and increased perfusion (function) in single-photon emission computed tomography (SPECT) scan.⁷⁴ Long-term use of dietary flavanols may improve cognition in mTBI.⁷⁵

Transcranial magnetic stimulation

Transcranial magnetic stimulation (TMS) has shown some promise in animal models of TBI.⁷⁶ However, a Cochrane review of the clinical application of TMS for depression noted no difference between repetitive TMS (rTMS) and sham rTMS using the Beck Depression Inventory (BDI) or the Hamilton Depression Rating Scale, except during the initial 2-week period.⁷⁷ The application of TMS in the post-TBI patients is limited by the risk of seizure induction.⁷⁸

Hyperbaric oxygen

Hyperbaric oxygen treatment has been explored as a treatment for TBI.^{79–91} Hyperbaric oxygen therapy is neither a benign treatment, given the concerns of oxygen toxicity,⁷⁹

nor a clear treatment in that the placebo condition of moderate hyperbaric room air also effectively improves cognitive function.^{80,81} The most carefully performed study compared a group in a cross-over design with an interval of both null treatment and hyperbaric oxygen at 100% oxygen and 1.5 atm.⁸² The study described improvement in many of the symptoms associated with persistent TBI including headache, tinnitus, vision disturbance, memory dysfunction, and impaired cognitive function. Cognitive testing also showed improvement in attention, information processing speed, and a battery of cognitive tests. In an uncontrolled case series of 16 subjects, Harch et al⁸³ demonstrated that an abbreviated series of hyperbaric treatments using 100% oxygen at 1.5 atm could mitigate subjective symptoms of TBI (eg, headache, sleep disruption, irritability), improve cognitive testing scores, and improve cortical function based on SPECT imaging.⁸³ A study of a higher dose (2.4 atm) did not reveal any significant benefit of hyperbaric oxygen therapy compared to a sham-control group treated with 1.3 atm,⁸⁴ and this result has been extended and confirmed by a related group.⁸⁵ However, this may reflect an inverse dose–response curve, rather than an absence of benefit, in that the low-dose sham group demonstrated significant changes in cognitive testing and symptom frequency.⁸⁶ Hyperbaric oxygen remains a controversial area in both acute TBI^{86–89} and chronic TBI.^{82,83,85,86,90,91}

Physical exercise

High-energy activities and exercise programs completed through a health club facility or comprehensive rehabilitation program should focus on the same parameters of an age-adjusted and diagnosis-specific program for aerobic conditioning – flexibility, stabilization, and strength. Though it appears safe and is an accepted intervention for TBI, there is a need for further well-designed studies.⁹² Exercise was a part of a 6-month study of lifestyle changes described above which yielded improved function based on cognitive testing and perfusion SPECT scans.⁷⁴

A new treatment for TBI

Unfortunately, little has been found to reverse the damage of TBI or repetitive concussion which is the root cause of residual cognitive and psychological impairment following TBI.^{20,93} One potential avenue of treatment for TBI is infrared light, which has shown promising data in a number of applications. Near-infrared (NIR) light has been investigated for its ability to modulate intracellular mechanisms related to healing. The application of NIR light by low-power laser or by light-emitting diode (LED) is also known as laser

phototherapy⁹⁴ or near-infrared photobiomodulation.⁹² NIR irradiation can facilitate wound healing,^{95,96} promote muscle repair,⁹⁵ and stimulate angiogenesis.^{95,96} NIR phototherapy has been studied and applied clinically in a wide array of ailments, including skin ulcers,⁹⁷ osteoarthritis,⁹⁸ peripheral nerve injury,^{95,96} low back pain,⁹⁹ myocardial infarction,¹⁰⁰ and stem cell induction.¹⁰¹

The finding that NIR light passes relatively efficiently through bone has spurred interest in its application to treating disorders of the brain. Over the past decade, transcranial near-infrared light therapy (NILT)¹⁰² has been studied in animal models to understand its ability to repair damaged or dysfunctional brain tissue resulting from stroke and TBI. The first published study of NILT for TBI in humans described two cases of chronic mTBI with significant disability.¹⁰³ Each patient was treated with an LED device delivering low-level low-level light therapy (LLLT) in the red and NIR range for 6–10 minutes per area daily for several months. Both patients had marked neuropsychological improvement after a minimum of 7–9 months of LLLT treatment.

The precise mechanisms underlying photobiomodulation and its therapeutic benefits are not fully understood.

The purported effects of NIR are illustrated in Figure 1. Light in the wavelength range of 600–1,200 nm has significant photobiomodulation capability.¹⁰⁴ Current data most strongly support that absorption of NIR photons by cytochrome c oxidase in the mitochondrial respiratory chain is the key initiating event in photobiomodulation.^{95,96,104,105} This induces an increase in cytochrome c oxidase activity which in turn increases adenosine triphosphate (ATP) production. Such an increase in ATP in wounded or underperfused cells may be sufficient to activate cells in areas of injury or metabolic derangement.¹⁰⁶ Data from numerous tissue culture and animal studies point to the importance of several secondary molecular and cellular events. For example, NIR photonic energy can modulate reactive oxygen species,^{95,96,102} activate mitochondrial DNA replication,^{95,96} increase early-response genes,⁹⁵ increase growth factor expression, induce cell proliferation, and alter nitric oxide levels.^{95,96,102} These mechanisms are more fully described in the companion paper.¹⁰⁵

When examined in the specific model of neural tissue injury, NIR phototherapy can lead to demonstrable neural repair and recovery. For example, LLLT of a power density of 0.9–36 J/cm² applied at 24 hours poststroke in a rodent

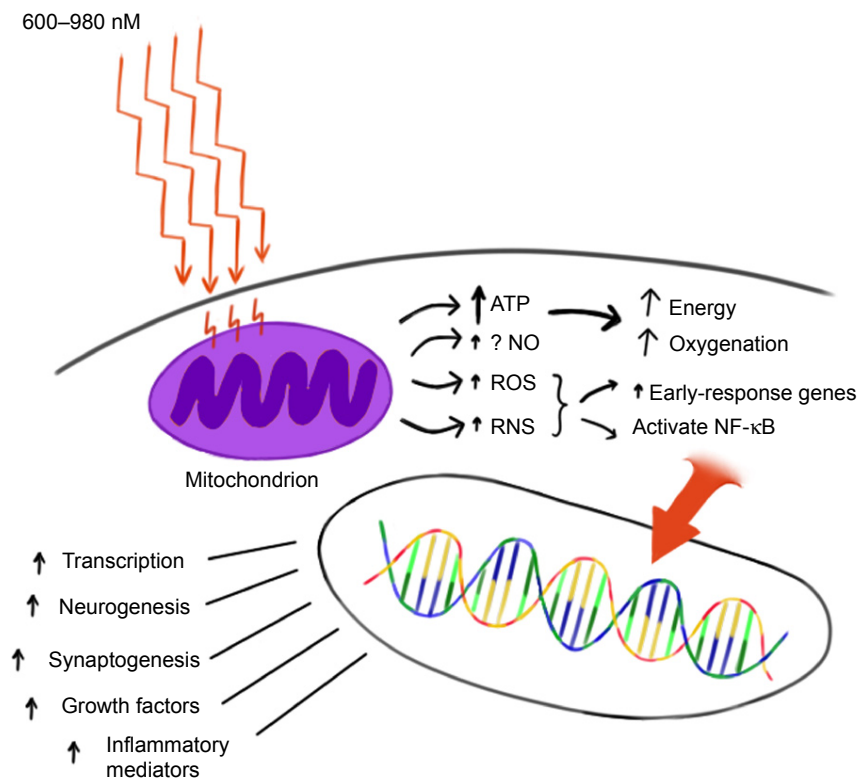


Figure 1 Hypothesized mechanism of action of NIR light therapy.

Notes: NIR light (600–980 nm) penetrates tissue to variable depths depending on wavelength, the tissue involved, coherence, and time. A fraction of the photonic energy reaches the mitochondria and is absorbed by cytochrome c oxidase. This activates increased ATP production, increases production of ROS and RNS, and possibly increases NO. Downstream events include increased early-response genes (*c-fos* and *c-jun*) and activation of NF-κB, which in turn induces increased transcription of gene products leading to synaptogenesis, neurogenesis, and increased production of inflammatory mediators and growth factors.

Abbreviations: NIR, near-infrared; ATP, adenosine triphosphate; ROS, reactive oxygen species; RNS, reactive nitrogen species; NO, nitric oxide; NF-κB, nuclear factor kappa B.

model yielded a 32% reduction in neurological deficits, as well as histochemical evidence of neuron proliferation and migration.^{106–108} LLLT had similar benefits in a rodent model of TBI.^{96,109–111} Interestingly, these cellular changes evolved over a period of days after light exposure and persisted for considerably longer than the interval of actual NIR exposure. These findings are consistent with a progressive regeneration cascade set in motion by the NIR light exposure.

NILT in stroke

NILT, predominately in the form of LLLT, has been investigated in laboratory models of stroke. LLLT applied in a single dose to an ischemic stroke model appeared to induce expression of the growth factor transforming growth factor-beta 1 and suppress the production of peroxynitrite.¹¹² In a rat model of middle cerebral artery occlusion, LLLT at a dose of 0.5–7.5 mW/cm² using continuous wavelength light at 808 nm was administered at 24 hours after the acute stroke.^{108,113} This single application was estimated to deliver 1.8 J/cm² in total to the cortex surface and resulted in demonstrable neurological improvement. Functional changes were not manifested until approximately 2 weeks after the single treatment. While there was no significant change in the size of the stroke lesion, histochemical evidence of neurogenesis and migrating neurons¹⁰⁸ indicate that a cascade of secondary processes was initiated by NILT. A rabbit model of stroke utilizing injection of a blood clot embolus also demonstrated benefit from LLLT.^{102,114,115} Herein, 808 nm light was applied with an LED delivering 7.5 mW/cm² and an estimated 0.9–2.6 J/cm² to the cortical surface. Cortical ATP levels were increased, indicative of increased mitochondrial activity.¹¹⁴ Significant behavioral recovery was also noted; however, neither ATP increased nor neurological function changed at doses less than 0.3–0.7 J/cm².^{114,115} At higher doses of 0.9–15 J/cm², neurological improvement was seen.^{114,115}

The clinical trials of NILT in acute stroke, the NeuroThera Effectiveness and Safety Trials 1, 2, and 3 (NEST-1, -2, -3), were conducted between 2006 and 2009. The Phase II clinical trial (NEST-1) involved 120 patients in a double-blind, placebo-controlled study of the effects of NILT within 24 hours of ischemic stroke.^{116,117} Approximately 60% of the patients experienced clinical benefit, and the safety profile was very good. Thus, NEST-2, a Phase III clinical trial, was undertaken in 2007. A total of 660 patients were enrolled.¹¹⁸ Somewhat surprisingly, the study did not demonstrate statistical clinical improvement using a different outcome measure.¹¹⁹ Post hoc analysis revealed that a portion of the patients who were moderately affected and/or had strokes limited to the cerebral cortex did realize clinically and

statistically significant improvement.¹⁰² The NEST-3 trial was halted midpoint when it failed to demonstrate statistical benefit on futility analysis.¹²⁰

A key factor in the interpretation of the results of NEST-3 is that, different from NEST-1, all types of stroke were included as opposed to just cortical strokes. Continuous laser light has a limited depth of penetration (≤ 1 cm into brain tissue) which likely prevents an effect on deeper brain matter. Therefore, the lack of significant benefits from NIR phototherapy in NEST-3 could be related to the fact that ischemic penumbra was not reached by the light (Luis DeTaboada, personal communication, January 2015). While pulsed NIR was not used in the NEST-3 study, it is estimated that pulsed NIR could penetrate up to 3 cm in depth from the cortical surface, therefore possibly extending the therapeutic target to deeper strokes (Luis DeTaboada, personal communication, January 2015).

NILT in TBI

Oron et al¹⁰⁹ conducted the first animal studies of NILT for TBI. They found that a single application of NIR light at 808 nm from a 200 mW emitter at 4 hours post-injury resulted in a significant reduction in lesion size by 5 days.¹⁰⁹ To date, several groups have studied NILT in animal models, and this material has previously been reviewed.^{95,121–123} Single applications of 800–810 nm NIR light within 4 hours of injury have been shown to improve neurological function significantly.^{110,124–126} The same dose of NIR light at 6 hours was less effective¹²⁵ and at 8 hours had no appreciable benefit.¹²⁵ NIR photonic energy at other wavelengths was less effective. Wu et al¹¹⁰ examined red light (670 nm) at 4 hours and found a similar improvement in neurological function; however, 730 nm and 980 nm had no neurological benefit. Similar data for lesion volume have been reported. A single dose of 800–810 nm NIR light (fluence of 36 J/cm²) yielded an approximate 50% reduction in the volume of the lesion at 3–4 weeks^{110,111,124–126} and a possible reduction in the initial spread of neurological injury, based on the marked reduction in lesion volume found at 5 days post-injury.¹⁰⁹

Repeated NIR phototherapy treatments appear to have some benefit, but the frequency and number of treatments are critical factors. While a single NIR light application had benefit, daily applications for 3 days yielded much greater neurological benefit^{126,127} with smaller lesion size,¹²⁶ fewer degenerating neurons,¹²⁶ more proliferating cells,¹²⁶ and greater levels of brain-derived neurotrophic factor (BDNF)¹²⁷ compared to a single treatment in a mouse model. In contrast, daily treatment for 7 days¹²⁸ or 14 days¹²⁶ showed no difference from controls. NIR energy densities in the range

of 0.9–36 J/cm² resulted in significant biochemical and behavioral changes.^{109–111,124–127}

Pulsing of NIR light appears to yield a greater neurological response but only within certain parameters. Pulsing at 10 Hz yielded greater neurological improvement and a significant reduction in lesion size compared to either continuous-wave or pulsed NIR at 100 Hz.¹¹¹ In the mouse model of moderate TBI, NILT (800–810 nm) improved learning and memory (Morris water maze performance),¹²⁸ as well as behaviors associated with depression and anxiety (immobility during tail suspension).^{111,124}

The finding that NILT brought about a smaller lesion in the rodent model of TBI compared to untreated mice suggests that decreased apoptosis, reduced spreading lesion penumbra, and/or neurogenesis are induced by NILT. Indeed, NILT can decrease *BAX* expression, a pro-apoptosis gene,¹²⁹ increase expression of *BCL-2*, an anti-apoptosis gene,¹²⁹ increase nerve growth factor,⁹⁵ increase BDNF,¹²⁷ decrease inflammatory markers,¹³⁰ and decrease numbers of degenerating neurons.¹²⁶ Together, these mechanisms may reduce the enlargement of the initial lesion during the first day following the lesion.¹⁰⁹ Moreover, increased BDNF and nerve growth factor may contribute to synaptogenesis as shown by increased levels of synapsin-1,¹²⁷ and neurogenesis, as shown by increased numbers of proliferating cells.¹²⁷

In a double-blind study in healthy volunteers, NILT was beneficial – compared to sham – in memory and attention.¹³¹ In this study, the authors shed only one application of NIR light to the right forehead, targeting the right frontal pole of the cerebral cortex (Brodmann's area 9 and 10). The device was a Class IV laser CG-5000 (Cell Gen Therapeutics, Dallas, TX, USA), and the parameters were as follows: wavelength 1,064 nm, irradiance 250 mW/cm², fluence 60 J/cm², and time 4 minutes per site (two sites).¹³¹ The subjects who received the NIR treatment had better attention after 2 weeks, measured by the psychomotor vigilance test. They also had better delayed visual memory at the Delayed Match-to-Sample test. This is the only published controlled trial assessing the impact of NILT on cognition; however, other reports have shown the therapeutic effects of NILT in small numbers of TBI patients.

In a two-case report in TBI patients,¹⁰³ NILT (870 nm) improved sustained attention, memory, and executive functions. Both patients were treated with an instrument with three separate LED cluster heads. The parameters used for the treatment were the following: NIR wavelength 870 nm and 633 nm (red light), irradiance 22.2–25.8 mW/cm², fluence 13.3 J/cm², and time 10 minutes per site.¹⁰³

The same group reported on a cohort of eleven subjects with persistent cognitive dysfunction and treated with a

similar NILT protocol for chronic mTBI.¹³² The eleven subjects received NILT with a device with three LED cluster heads (Model 1100; MedX Health, Toronto, ON, Canada). The parameters used for the treatment were the following: NIR wavelength 870 nm and 633 nm (red light), irradiance 22.2 mW/cm², fluence 13 J/cm², and approximate time 10 minutes per site. The NIR light was applied three times per week for 6 weeks (18 sessions), on eleven sites for 10 minutes per site (the total duration of each session was 20 minutes).¹³² The sites on the skull were chosen on the midline, and bilaterally on frontal, parietal, and temporal areas. At the follow-up neuropsychological testing, NILT had a powerful effect on attention, inhibition, and inhibition switching in the Stroop task, and similarly improved verbal learning and memory, as well as enhanced long-delay free recall on the California Verbal Learning Test.

Eight subjects, from the same cohort, were identified as having mild, moderate, or severe depression based on the BDI-II total score (range: 15–34).¹³² The three cases, who entered the study with only mild depression, remained the same after NILT treatment. Results for the five cases with moderate–severe depression were as follows: two moderate cases improved to mild/minimal depression 8 weeks after the end of NILT series, and one severe case improved to moderate depression. Two moderate or severe depression cases remained the same after 8 weeks of follow-up from the last NILT session.¹³²

Dose response and photonic penetration

A prevailing theory in photobiomodulation postulates that a bimodal response curve exists for the biological effects of NIR light.⁹⁵ The so-called Arndt–Schulz curve (a fundamental principle in homeopathic medicine) is frequently used to describe this biphasic dose response. Some data indicate that low levels of light have a much better effect on stimulating and repairing tissues than higher levels of light. Laboratory studies of cells in culture have demonstrated a bimodal dose response to light exposure in lymphocytes¹³³ and fibroblasts.^{134,135} For example, Chen et al¹³⁵ found that a range of 0.03–0.3 J/cm² was beneficial in activating transcription factors in culture, while 3–30 J/cm² inhibited the activation of these factors. In contrast, an order-of-magnitude greater dose (2 J/cm²) was best at activating fibroblasts in a superficial wound model.¹³⁶ Furthermore, an order-of-magnitude greater dose (30 J/cm²) proved to be best in a rodent joint inflammation model.¹³⁷ Thus, a dose-dependent effect for many biological responses to NIR light has been demonstrated,^{95,137–139} but the critical parameter is dose at the

level of the target tissue, rather than at the surface.^{137,140} The amount of energy that reaches a volume of tissue at depth is determined by the attenuation of the photonic energy as it passes through the overlying tissue. For example, only 2.45% of the energy from a 980 nm laser emitter penetrates to the level of the peroneal nerve.¹⁴⁰ Nevertheless, the biphasic dose response does not appear to be universally true. In primary microglial cell culture, a dose-dependent response to NIR was demonstrated with no detrimental effects at doses as high as 30 J/cm².¹⁴¹

So a critical question in the use of NILT is that of radiant energy penetration. In particular, some authors have challenged the efficacy of low-power LEDs used in LLLT.^{142–144} In laboratory studies, LLLT radiant energy is almost entirely absorbed in the first 1 mm of skin.^{145,146} In two unrelated studies, LLLT diode devices proved to be ineffective in the treatment of diabetic neuropathy,^{142,144} in contrast with prior reports.¹⁴⁷ Similarly, laboratory studies of NILT using LLLT transcranially have not consistently yielded positive results. For example, in a rat model of TBI, Giacci et al¹⁴⁸ found no benefit from daily 30-minute irradiation with either 670 nm or 830 nm 0.5 W LED emitters for a period of 7 days. Doses at the skin surface were 28.4 J/cm² and 22.6 J/cm², respectively.¹⁴⁸ Similarly, treatment of a rat model of contusive spinal cord injury with LLLT (830 nm at 22.6 J/cm² or 670 nm at 28.4 J/cm²) for 30 minutes per day for 5 days resulted in no significant functional improvement and no reduction in lesion size, despite delivering 2.6 J/cm² to the spinal cord.¹⁴⁸

Lapchak¹⁰² reported that the physical parameters of NILT in the clinical trials for the treatment of stroke utilized in the NEST-1 and NEST-2 trials^{116–120} may have delivered insufficient energy to cortical tissues to be effective. Therein, NIR light of 808 nm wavelength with infrared energy densities of 0.9 J/cm² was applied to the human scalp for a total of 40 minutes with applications at multiple sites during that time.^{116,118} Recall that animal models of both stroke and TBI suggest that NIR energy densities in the range of 0.9–36 J/cm² resulted in significant biochemical and behavioral changes.^{96,106–115,125–127} The concern raised from the NEST studies¹⁰² is that current clinical trials testing the effectiveness of low-energy NIR diodes to treat TBI may yield negative or inaccurate efficacy data, not because of a failure of infrared light to invoke a change but due to a dose error. Doses that are effective when directly applied to cells in a Petri dish^{149,150} or to 3–5 mm thick rodent brains^{96,109–111,125,126,128} may be insufficient to penetrate 2–4 cm into the human brain.

In a companion paper, our own studies of photonic energy penetration are detailed.¹⁰⁵ To summarize, the laboratory tissue

studies showed that 0.5 W LED emitters did not penetrate the 2 mm thickness of human skin. No detectable energy from 0.5 W LED NIR light emitters could be detected penetrating a similar thickness (1–2 mm) of sheep skin or 3 cm thick section containing sheep skin, skull, and brain. In contrast, 11% of the photonic energy from a 10 W 810/980 nm coherent NIR laser penetrated 2 mm of human skin. Similarly, 17% of the photonic energy from a 15 W 810 nm coherent NIR laser penetrated the same distance.¹⁰⁵ Energy from these more powerful NIR emitters could be detected penetrating 3 cm of sheep skin, skull, and brain with 0.4% of the 10 W 810/980 nm NIR laser's energy reaching the depth of 3 cm and 2.9% of the 15 W 810 nm NIR laser's energy traversing the same distance.¹⁰⁵ Anders also has demonstrated penetration of 808 nm light to 40 mm in the brain using a 5 W laser emitter (JJ Anders, personal communication, January 2015). Prompted by the mixed results in the literature and the observations by Lapchak,¹⁰² Franzen-Korzendorfer et al,¹⁴⁴ Wan et al¹⁵¹ and Lavery et al¹⁴² we have been utilizing relatively high-power (10–15 W) lasers at the wavelengths of 810 nm and 980 nm in the clinic to treat patients with TBI. Clinically, the patients have shown excellent responses with resolution of many of their long-standing symptoms of TBI or post-concussive syndrome. Below is a retrospective series of such patients to illustrate the extent and character of response to this modality.

Methods

Patients in the case series were sequentially treated patients at a clinic which is engaged in ongoing NILT for a number of clinical conditions. The risks, benefits, and current state of research on the use of NILT were explained to each patient. Each patient consented to treatment. Institutional Review Board approval was obtained in a post hoc review, noting that the risk–benefit ratio was acceptable.

Between March 16, 2011 and February 20, 2013, sequential new referrals for chronic mild-to-moderate TBI were evaluated for treatment and selected for NILT using Class IV lasers, either the LT1000 (LiteCure, Newark, DE, USA), a 10 W adjustable NIR laser emitter with wavelengths of 810/980 nm capable of delivering continuous or pulsed NIR light, or the Diowave 810 (Diowave, Riviera Beach, FL, USA), an adjustable NIR emitter up to 15 W with a wavelength of 810 nm capable of delivering continuous or pulsed NIR energy. Demographics and laser treatment settings are detailed in Table 1. The fluence delivered to the skin of patients ranged from 55 J/cm² to 81 J/cm². No other treatment modalities (medications, exercise regimen, supplements) were added, discontinued, or changed while receiving NILT. Symptoms

were monitored clinically. A baseline Quick Inventory of Depressive Symptomatology Self-Report (QIDS-SR)¹⁵² was completed for all patients, and the BDI¹⁵³ was administered to seven of the ten patients before and after the course of treatment. In addition, each patient was instructed on how to create and maintain a patient and spousal diary of symptoms and subjective progress. Each of six patients received a single series of ten treatments with the LT1000 Class IV laser. Three additional patients each received a single series of 20 treatments with the LT1000 Class IV laser. One patient was treated with the Diowave 810 nm Class IV laser device in a series of 20 treatments. The patients and treating clinician wore protective eyewear. There were no incidents of burns or thermal discomfort (Figure 2).

The impact of high-watt NILT

While the patient group represented a diverse mix (Table 1 presents demographics), some notable commonalities of symptoms emerged. Over 90% of the patients had complaints of anxiety, depression, irritability, and insomnia. Other symptoms included headache (60%), suicidal ideation (50%), cognitive difficulties (50%), attention problems (50%), short-term memory problems (40%), loss of libido (30%), substance abuse (20%), fatigue (20%), and panic attacks (20%). Six of the patients were unemployed prior to treatment. Three of the patients were experiencing severe marital difficulties. All carried or had a confirmed diagnosis of TBI, but other comorbid diagnoses included PTSD, major depressive disorder, generalized anxiety disorder, bipolar disorder, and attention deficit/hyperactivity disorder. The patients' baseline scores on the BDI were 25.3 ± 12.1 (moderate depression range), and baseline scores on the QIDS-SR were 12.9 ± 4.6 (moderate depression range).

During NILT treatments, skin temperature increased no more than 3°C with rapid cooling after removal of the NIR light. A continuous sweeping motion was utilized to minimize skin heating and cover a larger area. After a course of ten treatments of NILT (20 treatments in four patients), each patient experienced significant clinical improvement with resolution of many of their symptoms (Table 2). In addition, the BDI scores dropped to 12 ± 6.5 (nondepressed range). This represented a significant decrease ($P < 0.01$, Student's *t*-test, one-tailed, Microsoft Excel). The QIDS-SR scores after treatment were 2.2 ± 2.3 (nondepressed range), and the difference from baseline was highly significant ($P < 0.00001$, Student's *t*-test, one-tailed). Patients noted improvement in cognitive function, mood, anxiety, and sleep. None of the patients continued to have suicidal thoughts (50% at

baseline). Other symptoms, such as anxiety and irritability, were markedly improved. Most notable were the nonquantifiable changes in patients' lives. Patients reported improved cognitive ability and a desire to return to meaningful work. Five of the six unemployed patients have returned to work. The two patients who were Iraq/Afghanistan veterans have found new careers in highly skilled trades. The patients with marital difficulties have reconciled and were purchasing homes or otherwise solidifying their marriages. The clinical change can be attributed to NILT because no changes in medications, supplements, or exercise regimen were permitted during the course of NILT treatment.

All patients in the case series experienced significant clinical improvement which supports the conjecture that high-power NIR laser delivers sufficient energy to the human brain for photobiomodulation to occur. Insomnia and suicidal ideation, common symptoms in those with TBI or post-concussive syndromes,^{3,17–20,24,25} resolved in 100% of cases. Headache, another common symptom for patients following a TBI,^{6,14,15,23} was reduced or resolved in the six patients so afflicted. Symptoms such as anxiety,^{14,15,21,24} depression,^{21,24,25,27–29} and irritability resolved or were dramatically reduced in all patients. Cognitive function appeared to improve based on return to work or improved work performance, although cognitive tests were not performed. The quality of life dramatically improved in all cases, based on the observations of the patients, their family members, and the treating clinician.

At follow-up intervals of 6–7 months posttreatment, patients have reported continued improvements in symptoms. The precise areas of brain injury were not elucidated in the majority of these cases, so a correlation of symptoms changes and cortical function changes cannot be made; however, perfusion SPECT imaging in other patients has shown significant increases in perfusion in injured areas of the brain and overall improved cortical function following similar courses of high-watt NILT.¹⁵⁴

One concern that has been expressed about high-watt NIR lasers is the risk of tissue heating.¹⁵⁵ We explored this issue in our companion paper on NIR penetration.¹⁰⁵ Temperature change was 1°C–3°C at the skin surface using continuous-wave NIR lasers in the range of 10–15 W. Using pulsed settings, the high-powered lasers showed no significant temperature change in tissue samples. The temperature change on human skin was 1°C or less in the *in vivo* penetration studies while maintaining continuous movement of the laser probe head.¹⁰⁵ Clinically, patients in this case series reported only slight warming of the

Table 1 Infrared light treatment parameters for each of the ten patients in the case series

Patient	Area treated	Sex	Mechanism of TBI	Interval since TBI before treatment	Wavelength of NIR-PT dual wave	Dosage per area		Duration per area
						Scanning technique pulsed 10 Hz		
1	B, bilateral frontal	Male	Concussive blast	2 years	810 and 980 nm	2,700 J	Fluence – 20.45 J/cm ²	10 minutes
2	B, bilateral frontal	Female	MVA	18 years	810 and 980 nm	Area – 132 cm ²	Fluence – 18 J/cm ²	2 areas
						2,400 J	Area – 133 cm ²	10 visits
3	B, bilateral frontal	Female	MVA Abuse	5 years	810 and 980 nm	2,400 J	Fluence – 18.3 J/cm ²	2 areas
4	A–B, bilateral frontal, left temporal	Female	MVA ×2	8 years and 13 years	810 and 980 nm	Fluence – 18.3 J/cm ²	Area – 131 cm ²	10 visits
						2,400 J	Fluence – 18.3 J/cm ²	8 minutes
5	B, bilateral frontal	Male	Vietnam veteran Concussion	20+ years	810 and 980 nm	Area – 131 cm ²	Fluence – 28.3 J/cm ²	3 areas
						3,000 J	Area – 106 cm ²	10 visits
6	B, bilateral frontal	Male	Child abuse Concussion	5+ years	810 and 980 nm	2,400 J	Fluence – 14.8 J/cm ²	12 minutes
						Fluence – 14.8 J/cm ²	Area – 162 cm ²	2 areas
7	B–A, bilateral frontal, left temporal	Male	Afghanistan, Iraqi Disability due to TBI	Disability 2 years	810 and 980 nm	3,000 J	Fluence – 22.7 J/cm ²	10 visits
						Fluence – 22.7 J/cm ²	Area – 132 cm ²	3 areas
8	B–A, bilateral frontal, bilateral temporal	Female	Hypoxic encephalopathy	Childbirth-related injury, 8 years	810 and 980 nm	Area – 132 cm ²	Fluence – 27.8 J/cm ²	20 visits
						2,700 J	Area – 97 cm ²	9 minutes
9	B–A, bilateral frontal, bilateral temporal	Male	MVA-TBI Concussions	Numerous episodes	810 and 980 nm	Fluence – 27.8 J/cm ²	Fluence – 22.72 J/cm ²	3 areas
						Area – 97 cm ²	Area – 132 cm ²	20 visits
10	B–A, bilateral frontal, left temporal	Female	Bicycle vs car Concussion, amnesia, LOC	<30 days	810 nm single wavelength – different device	3,000 J	Fluence – 17.1 J/cm ²	10 minutes
						Fluence – 22.72 J/cm ²	Area – 158 cm ²	3 areas

Note: All safety precautions were followed, including metal protective eyewear (laser eye protection).
Abbreviation: LOC, loss of consciousness; MVA, motor vehicle accident; TBI, traumatic brain injury.

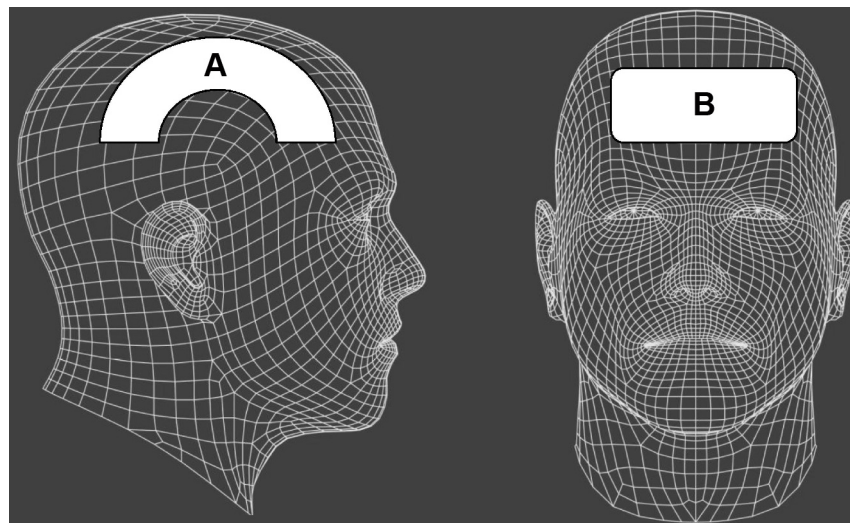


Figure 2 Treatment parameters per individual, based on area of the skull treated.

Notes: Dimensions varied per head/skull size and hair line. Treatment was warm and comfortable for each patient. There were no incidences of discomfort. Areas treated were (A) temporal-bilateral, (B) frontal, and in patients 1–3, 5, and 6 (B) frontal only.

skin, but no discomfort, using the continuous motion technique.

Laboratory studies have largely focused on treatment of acute brain injury. The processes involved in the benefits of NIR light in chronic TBI as seen in this clinical case series may be quite distinct. Nevertheless, Schiffer et al¹⁵⁶ found that a single application of LLLT at 810 nm and 250 mW to the forehead over 8 minutes reduced depression and anxiety symptoms in ten patients for approximately 2 weeks. Similarly, the small case series by Naeser et al¹⁰³ demonstrated some benefit using NIR light, albeit at very low power levels over a prolonged course of several months with only transient benefit. Together with our clinical data, these findings suggest that at least some of the photobiomodulatory effects of NIR energy likely do occur in chronic neurological conditions.

Prior presentations on NILT for the treatment of TBI or stroke in humans have focused on getting photonic energy through the skull to the cortex surface which traverses a distance of about 6–10 mm; however, this model is flawed in that the distance to the areas of damage may be far greater. In other words, the cortex immediately subjacent to a portion of the skull may be 10 mm from the surface, but the NIR light energy may need to penetrate 3–7 cm to reach areas of damage. Much of the cortical surface is actually lining the walls and floors of sulci, rather than immediately subjacent to the skull. Analysis of NIR spectroscopy reveals that light propagation through varying media with irregular boundaries is subject to high levels of scatter.¹⁵⁷ In addition, review of the neuroimaging literature on TBI has revealed that the most common areas injured in TBI are the orbitofrontal cortex (at

the ventral surface of the frontal lobe) and the anterior and medial temporal lobes.¹⁵⁸ It is not anatomically possible to position an NIR light emitter immediately exterior to the skull overlying these areas. Indeed, the orbitofrontal cortex positioned immediately above the eyes can only be reached from the forehead by angling the light emitter. Similarly, the temporal lobes are separated from the surface by epidermis, dermis, subcutaneous fat, subcutaneous blood vessels, accessory head of the temporalis muscle, connective tissue, temporalis muscle, skull, and dura mater.¹⁵⁹ Each of these structures has different absorption and refraction properties, and each interface between different materials also creates a barrier to transmission of photonic energy.¹⁵⁷ Blood flowing in the subcutaneous vessels is believed to create a unique barrier to transmission.¹⁶⁰ In summary, effectively targeting the areas most commonly injured in TBI with sufficient photonic energy to initiate reparative processes represents a significant challenge in NILT. This appears to have been overcome with the high-power laser protocol presented here and in a related paper.¹⁵⁴

As yet, the mechanism of action of NILT in treating TBI is not entirely clear. Moreover, the neurological benefits are not immediately apparent. Rather, a delay of 1–4 weeks was noted, consistent with a progressive regeneration cascade set in motion by the NILT.^{96,103,105,107,109,121,122,124,127,135} Similarly, most of the patients in the present case series did not notice benefits immediately or within the first few treatments. Instead, they reported benefits emerging over an interval of weeks, and in some cases, continuing after completion of the course of NILT. In addition, the clinical improvement

Table 2 NILT case series with demographics, symptoms, and treatment response

Pretreatment				Posttreatment								
Patient #	Sex	Occupation	Mechanism of TBI	Diagnoses	Sleep	Symptoms	Suicidal	BDI	Sleep	Symptoms	Suicidal	BDI
1	M	Veteran, unemployed	Blast – 5 years; Iraqi	TBI, PTSD, MDD	Primary and middle insomnia	H, S, I, D, X, L, A, M, C, SL	+	–	Resolved	None, back with spouse, working	No	–
2	F	Nurse, unemployed	MVA – 8 years	TBI, PTSD	Middle and terminal insomnia	H, F, I, X, C, A, StM, L, HA, SL	+	18	Resolved	A and HA – but mild, return to work	No	15
3	F	Unemployed	Assault and MVA, 5 years prior	TBI, PTSD, MDD, GAD, ADHD	Primary and middle insomnia, nightmares	D, X, P, M, L, HA, S, SA, C, N, StM	+	–	Resolved	HA – mild, back with spouse, no SA, working	No	–
4	F	Unemployed	MVA – 3 years, assault numerous	TBI, PTSD, MDD	Primary and middle insomnia, violent nightmares	D, X, HA, I, M, SA, S, N	+	23	Resolved	None, marriage improved, no SA, working	No	17
5	M	Veteran, unemployed	Blast – 20+ years 1960s; Vietnam	TBI, MDD, GAD	Primary and middle insomnia	D, X, I, S, SL	+	18	Resolved	None	No	1
6	M	Executive	Trauma – chronic	TBI, GAD, MDD	Primary insomnia	D, X, I, P, HA, A, S	–	–	Resolved	HA, X, and P – but improved	No	–
7	M	Veteran, disability	Multiple blasts (> 12); Afghan and Iraqi wars	TBI, MDD, GAD	Primary and middle insomnia	S, D, I, X, C, A, S, StM, HA	–	22	Resolved	HA and C – mild, new career	No	16
8	F	Student	Childbirth	TBI, learning disorder	Primary insomnia	D, I, X, C, A, SL, F, StM	–	16	Resolved, no bad dreams	StM improved, reading >20% more animated	No	7
9	F	Sales	MVA and sports TBI	TBI, LOC	Primary and middle insomnia, nightmares	HA, SL, N, D, I, X, H, A	–	29	Resolved	Mild HA, job promotion	No	9
10	F	Physicist	Recent car–bicycle accident	TBI, LOC, amnesia	Primary and middle insomnia	D, I, X, neck, knee pain	–	51	Resolved	No loss of skills, maintain intellectual job	No	19

Notes: Demographics for each of the ten patients in this case study is presented. Also presented is their history of mechanism of injury, diagnosis, and related symptoms. Changes in anxiety levels, sleep patterns, depression, and suicidal ideation were important symptoms and outcomes to track. Patients were instructed for no medication changes, with their primary treatment provider's approval. Cognitive difficulties, attention problems, and short-term memory difficulties were by patient interpretation of their symptomatic improvement and patient diary changes. Symptom occurrence % was as follows: anxiety – 100%, depression – 90%, irritability – 90%, primary and middle insomnia – 90%, headache – 60%, sadness – 60%, suicidal ideation – 50%, cognitive difficulties – 50%, attention problems – 40%, marital difficulties – 30%, loss of libido – 30%, substance abuse – 20%, fatigue – 20%, panic attacks – 20%.

Abbreviations: NILT, near-infrared light therapy; TBI, traumatic brain injury; PTSD, posttraumatic stress disorder; MDD, major depressive disorder; GAD, general anxiety disorder; ADHD, attention deficit/hyperactivity disorder; H, hyperarousal; S, sadness; I, irritability; D, depression; X, anxiety; L, loss of libido; A, attention problems; M, marital difficulties; C, cognitive problems; SL, sleep issues; F, fatigue; StM, short-term memory problems; HA, headache; P, panic attacks; SA, substance abuse; N, nightmares; BDI, Beck Depression Inventory; LOC, loss of consciousness; MVA, motor vehicle accident.

reported by the patients in the above case series is more profound than that reported by patients treated with LLLT or low-powered lasers.¹⁰³ In fact, we observed that among seven subjects with documented moderate depression, per BDI scores, four had an antidepressant response ($\geq 50\%$ decrease of depression severity). In contrast, Naeser et al¹³² reported that out of eight subjects with TBI and comorbid depression, only three had a significant improvement in their depressive symptoms (37.5%). Our results may be due to the greater penetration of more powerful, coherent, and pulsed NIR light from a laser source.

A unique outcome measure was developed for this protocol (Morries and Henderson, unpublished data, 2015). A patient diary and separate spousal diary provided a weekly update of patient's response in his or her home environment. This novel approach to capturing the patient treatment experience provided the patient and family with tangible and pertinent documentation of the clinical response. While time consuming, the experiences recorded in these diaries proved to be valuable clinical tools to the treating clinicians.

Conclusion

To date, there has been little progress in developing effective treatments for chronic mild-to-moderate TBI or repetitive concussions. This area of need has become even more pressing with the return of veterans from military conflicts in Iraq and Afghanistan^{4,6,7,16,17,19,161} and the recognition of the magnitude of sport-related TBI.^{5,8–10} In addition, the dramatic growth in the geriatric population with attendant proprioceptive dysfunction has resulted in a rising incidence of fall-related TBI.¹⁶²

NILT has shown promise as a tool for the treatment of TBI. A critical issue is to assure that adequate photonic energy reaches the injured areas of the brain. The use of high-wattage lasers, as we have demonstrated, results in marked clinical improvement in patients with chronic TBI. Moreover, symptoms consistent with PTSD, anxiety, and/or depression also improved considerably or resolved in this group of patients. Further work in the use of high-wattage NILT in the treatment of TBI, depression, and other neurological disorders is encouraged.

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Dr Larry D Morries is the CEO of Neuro-Laser Foundation, a nonprofit foundation. He has a private practice in Lakewood, CO. Theodore A Henderson is the president of The Synaptic Space, a medical consulting firm. He is the president of Dr Theodore Henderson, Inc., a clinical service firm. He is the co-owner of Neuro-Luminance, a clinical service organization. He is the president of the International Society of Applied Neuroimaging. He is the CFO of the Neuro-Laser Foundation, a nonprofit foundation. Dr Paolo Cassano received funding from the Brain and Behavior Research Foundation; Photothera Inc and from the Dupont Warren Fellowship (Harvard Medical School) to conduct research on NIR light for the treatment of major depressive disorder.

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