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Emerging neuromodulation treatments for opioid and stimulant use disorders

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Over the past decade, deaths attributable to opioid and stimulant use have risen dramatically. While the U.S. Food and Drug Administration (FDA) has approved three medications for opioid use disorder, there is currently no FDA-approved treatment for stimulant use disorder. Despite the availability of medications for opioid use disorder, the rates of relapse and overdose, particularly in the time of widespread fentanyl use, remain distressingly high. There is an urgent need for more effective treatment options for these debilitating disorders. This article provides an overview of the current standard of care for opioid use disorder and stimulant use disorder. New and emerging neuromodulation approaches with a particular focus on deep brain stimulation are then discussed.

KEYWORDS

substance use disorder, opioid use disorder, stimulant use disorder, addiction, brain stimulation, neuromodulation

1 Introduction

Over 45 million people in the United States (U.S.) meet the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) criteria for a substance use disorder (Portrait of American Healthcare, 2022). In the U.S., drug and alcohol use directly account for over 200,000 deaths annually (Ritchie et al., 2022). In 2019, 47,337 deaths in the U.S. were opioid-related–reflecting a 988% increase in opioid-related deaths since 1990 (Ritchie et al., 2022). While opioids have been responsible for the largest number of drug-related deaths, deaths associated with stimulant use have also risen dramatically in recent years. From 2012 to 2018, the rate of psychostimulant-related mortality increased by a factor of five (0.8–3.9 per 100,000 people) and cocaine-related mortality by a factor of three (1.4–4.5 per 100,000 people) (Ciccarone and Shoptaw, 2022). Increasingly, fentanyl has been intentionally introduced into the cocaine supply, (Di Trana et al., 2022) which has fueled a growth in co-occurring opioid and stimulant use and raised overdose rates (Ahmed et al., 2022).

The challenging treatment landscape compounds the devastating impacts of opioid use disorder (OUD) and stimulant use disorder (StUD). Buprenorphine, methadone, and naltrexone are U.S. Food and Drug Administration (FDA)-approved for the treatment of OUD; no existing treatments are FDA-approved for StUD (i.e., use of methamphetamine-type substances, cocaine, or misuse of prescription stimulants such as methylphenidate), causing significant impairment and distress. Furthermore, medications for substance use disorders are often difficult for patients to access conveniently and consistently

(Cantor et al., 2021; Park et al., 2024). Neuromodulation techniques such as repetitive transcranial magnetic stimulation (rTMS), deep brain stimulation (DBS), and low-intensity focused ultrasound (LIFU) are promising new treatment modalities for substance use disorders that target dysfunctional neurocircuitry at the core of the disorders. In this mini-review, we will summarize the current standard of care for OUD and StUD. We will then discuss new and emerging neuromodulatory treatments for these two substance use disorders.

2 Standard of care for opioid and stimulant use disorders

Three medications - buprenorphine, methadone, and naltrexone - are FDA-approved and target the mu-opioid receptor with unique mechanisms of action (Leshner and Mancher, 2019). Methadone is a full agonist of the mu-opioid receptor with a long terminal half-life (up to 120 h) that reduces opioid craving, withdrawal, and stress reactivity. Methadone maintenance therapy has the highest treatment retention rates (Connery, 2015) and is highly effective (six randomized controlled trials, RR 0.66, 95% CI: 0.56 – 0.78) (Mattick et al., 2009). However, methadone has sedating effects and is difficult for many patients to access due to the burden of mandated daily in-person visits to the limited number of opioid treatment programs (Mitchell et al., 2022). Buprenorphine is a partial mu-opioid receptor agonist that competitively blocks or decreases the reinforcing effects of other opioids (Connery, 2015; Mattick et al., 2014). Unlike methadone, buprenorphine does not require daily in-person dispensing, and new formulations can extend dosing – even as far out as every 6-months (Soyka and Franke, 2021). However, it is less successful in retaining patients in treatment compared to methadone (Mattick et al., 2014). The adherence rates to naltrexone, a mu-opioid receptor antagonist that competitively blocks the effects of opioid agonists, are even lower, which has limited the real-world utility of this medication (Connery, 2015). This non-addictive treatment requires a period of abstinence before initiation and does not appear to directly reduce opioid craving (Dijkstra et al., 2007).

There is currently no FDA-approved treatment for StUD, highlighting an urgent gap in care. The growing need is driven by a significant increase in stimulant-related morbidity and mortality in recent years, which has even prompted the FDA to produce draft guidance to encourage drug development in this area (Center for Drug Evaluation and Research [CDER], 2023). A meta-analysis of behavioral and medical treatments for cocaine use disorder found that contingency management, a treatment plan that provides monetary rewards for negative drug tests, was the only treatment category associated with an increased likelihood of a negative urinalysis for cocaine (odds ratio 2.13, 95% CI 1.62 – 2.80) (Bentzley et al., 2021). However, in one of the largest trials of contingency management, the abstinence rate among participants remained less than 20%, Petry et al. (2005) and its real-world availability is limited (Bentzley et al., 2021; De Crescenzo et al., 2018). Off-label pharmacologic treatments for StUD include anticonvulsants, antidepressants, antipsychotics, dopamine agonists, opioids, and psychostimulants, but none significantly increase the odds of achieving negative urinalysis (Bentzley et al., 2021).

3 New and emerging neuromodulatory treatments

3.1 Non-invasive brain stimulation techniques

Neuromodulation may fill the pressing unmet need for novel treatments by directly engaging dysfunctional circuitry (Figure 1) (Koob and Volkow, 2010, 2016). Table 1 includes studies of using non-invasive brain stimulation techniques for treatment of StUD and OUD. rTMS is a non-invasive method of neuromodulation that stimulates or inhibits neural activity by applying alternating magnetic fields to induce electric currents in underlying neurons in specific brain regions according to Faraday's law of electromagnetic induction. It is FDA-approved for treatment-resistant depression, obsessive-compulsive disorder, and migraine with aura. rTMS has also been shown to be effective for smoking cessation, leading to FDA clearance of the BrainsWay Deep TMS system in 2020 (Zangen et al., 2021). Research into rTMS as a potential treatment for other substance use disorders is ongoing. The most commonly targeted region is the left dorsolateral prefrontal cortex (DLPFC), with varying stimulation parameters and treatment durations. High-frequency rTMS to the prefrontal cortex is hypothesized to reduce craving and drug cue reactivity and improve decision-making in the preoccupation/anticipation stage of addiction (Gorelick et al., 2014). Large sham-controlled double-blinded trials of left DLPFC rTMS have demonstrated decreased drug craving among subjects with StUD (Liang et al., 2018; Su et al., 2017, 2020a, 2020b; Yuan et al., 2020). Left DLPFC rTMS has also been shown to be effective in reducing cue-induced craving in patients with OUD (Liu et al., 2020). A recent systematic review identified 18 studies including 985 patients [methamphetamine use disorder (n = 519), cocaine use disorder (n = 227), OUD (n = 239)] and showed mostly positive effects on cue-induced drug craving, though cocaine studies showed particularly mixed results (Mehta et al., 2024). The review highlighted several null or opposite effects of TMS on craving and found that little research has tested its effects on drug consumption. Statistically null results of some rTMS studies for substance use disorders could be the result of the type of coil employed (a figure-of-eight coil has a more focal stimulation field compared to an H-coil), inaccurate targeting, or strengthening of the sham/placebo effect with study visits and psychosocial support (Bolloni et al., 2016; Martinotti et al., 2022). Variable outcomes may also be attributable to suboptimal stimulation parameters and difficulty with retention in rTMS trials, which require daily treatments for up to 6 weeks (Brunoni et al., 2020). Advances in the delivery of neuromodulation may improve treatment efficacy and help address barriers to patient retention. Intermittent theta burst stimulation, a form of rTMS, has shortened treatment times while maintaining efficacy (Liu et al., 2022). In one of the largest rTMS studies for StUD, 126 participants with methamphetamine disorder were randomized to either 20 daily sessions of intermittent theta burst stimulation to the DLPFC or sham treatment (Su et al., 2020a). The theta burst stimulation group experienced a significant decline in cue-induced craving which was not observed in the sham group. This study could not assess the effect of theta burst stimulation on abstinence as it took place in a long-term residential treatment facility. Accelerated TMS

paradigms, where the full course of TMS is compressed into 5 days, have shown efficacy for depression (Cole et al., 2022) and may hold promise for substance use disorders. Such treatments could also be performed inpatient, which increases the likelihood of TMS course completion. One such study, evaluating the feasibility of accelerated rTMS for StUD and comorbid depression, is currently underway (NCT06424184). In addition to reducing craving, the effect of TMS on drug use abstinence and relapse is an important area for further study.

Other promising non-invasive brain stimulation techniques include transcranial direct current stimulation (tDCS) and transcranial alternating current stimulation (tACS). tDCS modulates cortical excitability via non-synaptic changes of the cells–including cathodal stimulation to decrease cortical excitability and anodal stimulation to increase cortical excitability via either hyperpolarization or depolarization, respectively, of the resting membrane potential (Stagg and Nitsche, 2011). While tDCS constantly depolarizes or hyperpolarizes neurons, tACS delivers fluctuating current between electrodes to induce synaptic plasticity (Elyamany et al., 2021; Gholamali Nezhad et al., 2024). In comparison to rTMS, tDCS and tACS do not require a magnetic coil and are delivered by relatively inexpensive, portable battery-powered devices (Elder and Taylor, 2014). This increases the accessibility of these modalities, however, unlike rTMS, tDCS and tACS are not able to focally deliver stimulation to specific targets. tDCS treatments (most commonly directed to the DLPFC) have been shown to reduce craving for stimulants [cocaine, (Batista et al., 2015; Klauss et al., 2018) methamphetamine (Shahbabaie et al., 2014; Shariatirad et al., 2016)] and heroin (Wang et al., 2016). tACS is a newer technology than tDCS and only two studies have tested it for substance use disorder indications. These studies applied alpha-tACS to the bilateral DLPFC, with one showing improved inhibitory control in people with a variety of substance use disorders (N = 30) (Daughters et al., 2020) and the other showing improved behavioral flexibility in people with prior substance use dependence (N = 17) (McKim et al., 2021). Research has yet to test the effects of tACS on OUD and StUDs or on drug use and craving.

3.2 Deep brain stimulation (DBS)

One limitation of currently available non-invasive brain stimulation techniques is the inability to directly target the subcortical brain structures involved in the reward and reinforcement circuit. DBS and LIFU can successfully reach deeper brain targets. Table 1 lists the outcomes of all reported studies of DBS and LIFU for the treatment of OUD and StUDs.

In DBS, electrical current is delivered to a deep brain region via implanted electrodes. It is a standard-of-care treatment for advanced movement disorders such as essential tremor and Parkinson's disease, and epilepsy with over 5,500 DBS operations performed each year in the U.S (Sarica et al., 2023). The electrodes are connected via extension wires to a pacemaker-like unit called an implantable pulse generator, which is typically placed subcutaneously in the chest wall. There are several proposed non-exclusive therapeutic mechanisms of DBS. One predominant theory is that the benefits of high-frequency [>130 Hertz (Hz)] stimulation arise from a reversible lesioning effect (Herrington et al., 2016). There is also increasing recognition that DBS modulates neural activity on a network level to effect dysregulated connectivity–the electrode target acting as a single node with upstream and downstream projections (Hollunder et al., 2024). Like TMS, DBS treatment involves multiple programming parameters (frequency, current amplitude, pulse width) that can be adjusted to maximize clinical efficacy and minimize side effects.

Pre-clinical studies have shown that nucleus accumbens (NAc) DBS reduces drug-seeking behavior in rodents (Eskandari et al., 2023; Guercio et al., 2015; Guo et al., 2013). Reinstatement testing, commonly used in animal studies of addiction, is designed to model relapse. After a period of drug self-administration followed by extinction training, drug-associated cues are re-introduced to test for drug-seeking behavior. Using this paradigm, Vassoler et al. (2008) demonstrated that DBS of the NAc shell reduced drug seeking in rats. Rats who received bilateral NAc DBS had lower the number of lever presses to trigger cocaine administration following reinstatement, suggesting attenuation of drug-seeking behavior with stimulation.

Several human studies in a small number of patients have demonstrated the feasibility of continuous NAc DBS for StUDs and OUDs (Table 1). Most studies showed that participants remained abstinent or reduced the amount and/or frequency of drug use. Across these studies, no serious adverse events were reported. Zhang et al. (2019) reported the results of bilateral NAc DBS in a patient with treatment-refractory methamphetamine disorder. Following 1 year of DBS treatment, the patient remained abstinent per self-report and urine and hair drug testing. The patient also had improvements in measures of craving, mood, anxiety, quality of life, and functional impairment. Positron emission tomography imaging obtained before and 1-year post-DBS implantation showed enhanced striatal dopamine transporter binding, suggesting a normalization of brain dopaminergic dysfunction. Rezai et al. (2024) conducted a prospective, open-label, single-arm study of bilateral NAc DBS in treatment-refractory OUDs. Two of the four patients were completely abstinent after surgery, one patient had recurrent drug use but decreased frequency and severity, and one patient had the DBS system explanted due to non-compliance with study protocols. In light of the promising early findings, several groups are now designing randomized-controlled trials to establish the safety and feasibility of NAc DBS for substance use disorder (NCT04354077).

DBS provides continuous treatment with a less demanding follow-up schedule than methadone maintenance therapy. However, frequent programming visits to optimize stimulation settings can be a barrier (Hunka et al., 2005). In 2020, the first fully remote DBS programming system received FDA approval, which may substantially improve the feasibility of this treatment option (Merola et al., 2021). Another recent advance is the commercial availability of devices with the capability to continuously record local field potentials, i.e., synaptic potentials of adjacent neurons at the implantation site. The ability to detect behaviorally relevant brain signals brings promise to closed-loop delivery of DBS only when needed (i.e., when a pathological signal is detected). Electrophysiological biomarkers of reward anticipation or craving have been identified in animals (Wu et al., 2018) and humans

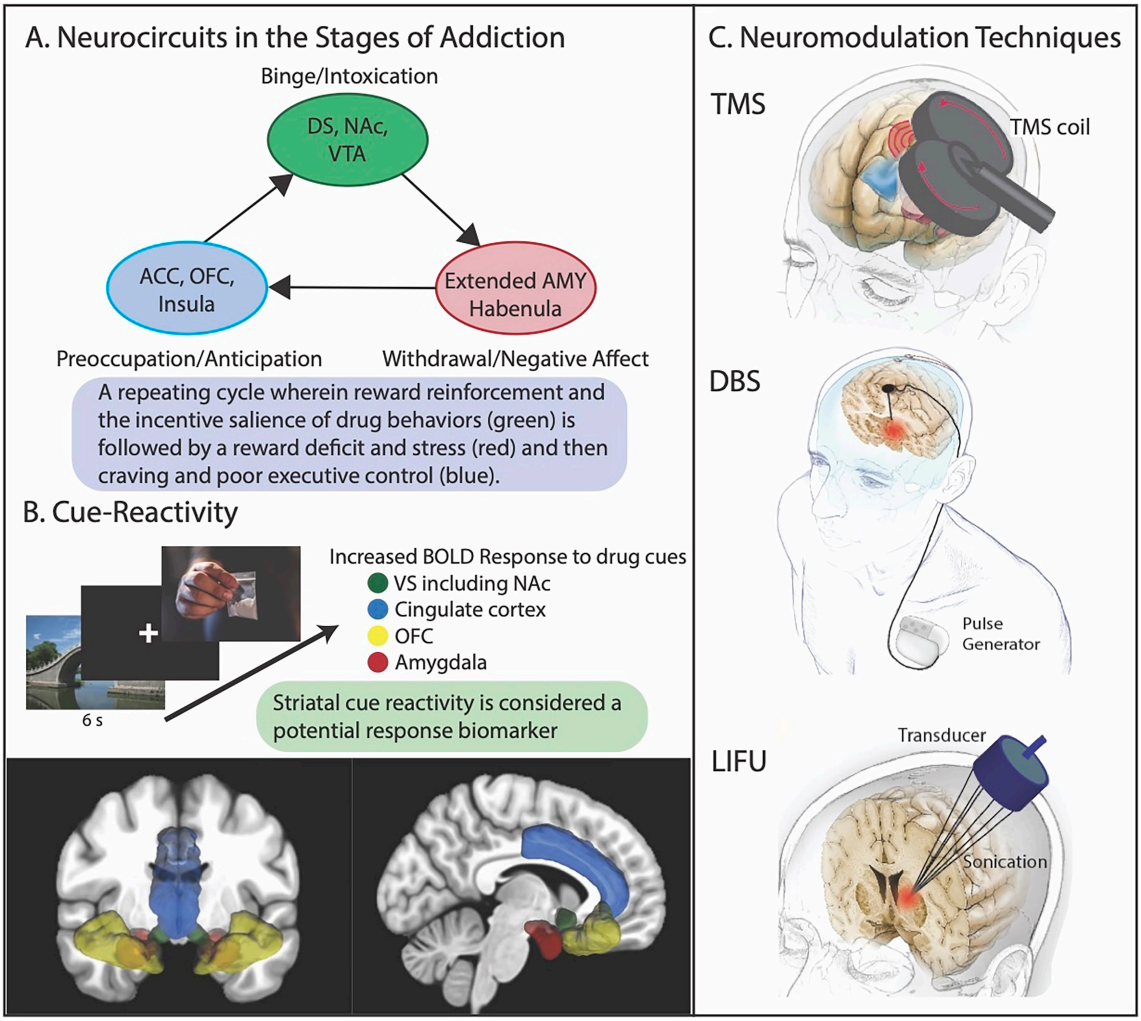

FIGURE 1
(A) Dysfunction within the mesocorticolimbic circuit, which processes rewards and punishments underlies substance use disorders. It is theorized that disturbances in three subcircuits underly the binge/intoxication, withdrawal/negative affect, and preoccupation/anticipation stages of addiction. **(B)** Brain reactivity to drug-related pictures during task-based fMRI studies. **(C)** The neuromodulation techniques available for treatment: transmagnetic stimulation (TMS), deep brain stimulation (DBS), and low-intensity focused ultrasound (LIFU). Abbreviations: amygdala (AMY), blood oxygen level dependent (BOLD), anterior cingulate cortex (ACC), nucleus accumbens (NAc), orbitofrontal cortex (OFC), ventral tegmental area (VTA).

(Nho et al., 2023) through the use of intracranial recordings and may potentially be integrated into new DBS technology (Chen et al., 2024). In closed-loop DBS, stimulation is delivered only when a biomarker is detected (responsive DBS), or stimulation is adjusted based on the presence or magnitude of a biomarker (adaptive DBS). In a patient with a history of OUD and StUD, we identified a drug-cue specific low-frequency (1–7 Hz) band electrophysiological signal in the left NAc shell (Qiu et al., 2024). This biomarker was not identified in other electrode contacts nor with other behavioral tasks. Stimulation in the NAc shell attenuated the power of this low-frequency band signal as well as clinical ratings of craving. This suggests the potential of using this low-frequency signal as a biomarker of craving, and ability to modulate this signal, and thus behavior, with DBS. The feasibility of closed-loop stimulation has been demonstrated in Parkinson's disease, epilepsy, and some neuropsychiatric conditions (Oehrn et al., 2024). Like the symptoms of Parkinson's disease, the urges and cravings associated with substance use disorder are often dynamic and context-dependent. Closed-loop capabilities can permit the identification and modulation of urge/craving states in real time. This flexibility would enable treatment of both background affective symptoms in addition to cue-reactive states to further enhance recovery. Other advantages of closed-loop stimulation include decreasing the total stimulation burden, which may reduce side effects, minimize tachyphylaxis phenomenon, improve outcomes, and facilitate neural plasticity.

3.3 Focused ultrasound

Low-intensity focused ultrasound is an exciting and new neuromodulation technique that can reach deep structures but, unlike DBS, does not require open neurosurgery or a device implant (Olaitan et al., 2024). While high-intensity focused ultrasound uses thermal energy to ablate surgical targets, LIFU is non-ablative and is thought to modulate neuronal activity

TABLE 1 Studies of non-invasive brain stimulation techniques [repetitive transcranial magnetic stimulation (rTMS), transcranial direct current stimulation (tDCS), transcranial alternating current stimulation (tACS)], deep brain stimulation (DBS) and low intensity focused ultrasound (LIFU) for stimulant use disorder and opioid use disorder.

Study	Drug of use	Intervention	Sample size	Results	Adverse events
Non-invasive brain stimulation techniques					
Batista et al., 2015	Crack-cocaine	Five sessions of bilateral DLPFC tDCS (left cathodal, right anodal)	17	Craving scores were significantly reduced in the treatment group compared to sham.	Mild side effects including altered scalp sensation (buzzing, tingling, burning).
Wang et al., 2016	Heroin	Single tDCS session to the bilateral frontal-parietal-temporal areas.	20	Cue-induced craving scores were significantly reduced in the treatment group whereas there was no changes in craving in the control group.	No side effects reported.
Yuan et al., 2020	Heroin	10-Hz and 1-Hz rTMS to the left DLPFC	118	Cue-induced craving was significantly reduced in treatment group compared to control group receiving no rTMS treatment.	Mild side effects including dizziness, headache, neck pain, insomnia.
Liu et al., 2020	Methamphetamine	1-Hz rTMS to the left prefrontal cortex	73	Impulse inhibition was significantly improved in the treatment group as well as reduced self-reported cue-induced craving compared to the sham group.	None reported.
Deep brain stimulation					
Zhou et al., 2011	Heroin	Continuous bilateral NAc DBS.	1	No relapse at 6-year follow-up. Improvement in memory scores, and reduction in depression and anxiety measures.	Mild confusion, urinary incontinence, weight gain.
Valencia-Alfonso et al., 2012	Heroin	Continuous bilateral NAC/ALIC DBS.	1	Six months without heroin use with exception of a 14-day relapse.	None reported.
Kuhn et al., 2014	Opioids (& methamphetamine)	Continuous bilateral NAc DBS.	2	Continuous abstinence with exception of one singular incident of heroin consumption for both patients. Follow-up time not reported.	Seizure in patient with prior history of seizures.
Gonçalves-Ferreira et al., 2016	Cocaine	Continuous bilateral ALIC/nucleus stria terminalis/NAc DBS. Three-phase crossover design.	1	At 24-month follow-up, 68% weeks free of consumption vs. 41% before and 56.5% negative urinalysis vs. 12% before.	Transient stimulation side effects.
Ge et al., 2019	Methamphetamine	Continuous bilateral NAc/ALIC DBS.	2	One participant without relapse at 1.5-year follow-up. Minimal effect in one participant who started intermittently relapsing at 6-month follow-up.	Transient hypomania, anxiety.
Zhang et al., 2019	Methamphetamine	Continuous bilateral NAc/ventral capsule DBS.	1	Abstinence for a full year.	None reported.
Rezai et al., 2024	Opioids (& benzodiazepines, cannabis)	Continuous bilateral NAc/ventral capsule DBS.	4	Two participants with complete abstinence. One participant with reduced frequency and severity of drug use. One participant had device explanted due to non-compliance with treatment requirements.	No serious adverse events or device- or stimulation-related adverse events.
Focused ultrasound					
Mahoney et al., 2023	Opioids	Two doses (60 and 90 W) of LIFU to bilateral NAc.	4	Two participants receiving 90 W LIFU dose had decreased craving 90 days following treatment. Urine toxicology was negative for opioids through 90-day follow-up for all four participants.	No serious adverse events.
Rezai et al., 2025	Opioid (& stimulants)	One dose (90–100 W) of LIFU to bilateral NAc	8	Five participants were abstinent at 90-day follow-up. The three participants who experienced relapse used drugs less frequently than their baseline use.	No serious adverse events.

ALIC, anterior limb of internal capsule; DLPFC, dorsolateral prefrontal cortex; NAc, nucleus accumbens; W, Watt.

through mechanotransduction effects and can excite or inhibit neuronal activity depending on the specific parameters. While still nascent in its development, a pilot open-label study including four participants with OUD who received LIFU [either 60 or 90 Watt (W) dose] to the bilateral NAc demonstrated safety and promising outcomes on craving (Mahoney et al., 2023). The two participants receiving the enhanced LIFU dose (90 W) had decreased craving for substances acutely and at 90 days following treatment. In a follow-up study (NCT04197921) of a similar but larger sample ($N = 8$), investigators again found reductions in cue-induced craving following 90–100 W sonication to the NAc and further showed sustained decreases in substance use (Rezai et al., 2025). Building on these results, there are currently five active LIFU studies for substance use disorder indications, including another study investigating the safety and tolerability of LIFU for OUD (NCT06218706) and one study seeking to understand the impact of LIFU on craving levels among patients with cocaine use disorder as evidenced by imaging of the dorsal anterior insula and subjective ratings (NCT05857852). This reflects the strong interests and growth of LIFU as a potential neuromodulatory therapy in substance use disorders.

4 Discussion

The current standard of care for patients with substance use disorders is severely lacking, leaving many patients refractory to existing therapies. The resulting morbidity and mortality are substantial and represent an unacceptable *status quo*. The dysfunctional neurocircuitry driving addiction is theoretically amenable to neuromodulation as a treatment, and the results from cases of neuromodulation in humans with severe, refractory substance use disorders are promising. However, the nature of this disorder challenges retention rates in complex treatment trials, which, together with a lack of consensus and standardization of reliable outcome measures and biomarkers, has hindered the necessary clinical development pathway to FDA approval.

Growing efforts seek to standardize the reduction in substance use rather than abstinence as a primary outcome measure. FDA draft guidance released in October 2023 highlights within-subject change in the pattern of drug use as an appropriate clinical trial endpoint (Center for Drug Evaluation and Research [CDER], 2023). Yet, the lack of reliability of self-report measures and the burden of frequent urine drug screens still remain as challenges. The use of multiple substances further complicates the outcomes for specific substances. As OUD and StUDs increasingly co-occur and involve overlapping neurocircuitry, there is a scientific rationale for neuromodulation trial designs that encompass both conditions. fMRI-cue reactivity is an exciting potential surrogate endpoint that is widely accepted by researchers in the field (Ekhtiari et al., 2022). Cue reactivity is a learned response to drug cues that triggers prefrontal cortex-driven craving along with conditioned activation of the subcortical motivational (reward) circuitry. Objective neuroimaging biomarkers of cue reactivity may help identify people at risk for recurrence and measure the progression and treatment of the disorder (Childress et al., 2008; Ekhtiari et al., 2024; Morales and Berridge, 2020). fMRI studies across substance use disorders consistently identify increased activity in the striatum, amygdala, PFC, and insula in response to drug cues, (Dejoie et al., 2023; Hill-Bowen et al., 2021; Huang et al., 2018; Moeller and Paulus, 2018; Regier et al., 2021; Yalachkov et al., 2012) which is associated with substance use severity, treatment outcomes, and risk of relapse (Janes et al., 2010; Jasinska et al., 2014; Li et al., 2015; Moeller and Paulus, 2018). While fMRI has high spatial resolution, the temporal resolution is poor compared to electroencephalography (EEG) (Houston and Schlienz, 2018). Event-related potentials (ERP), EEG brain signals measured in response to a specific stimulus, have been associated with treatment outcomes, relapse, and cue reactivity in patients with substance use disorders (Bel-Bahar et al., 2022; Habelt et al., 2020; Parvaz et al., 2017; Sokhadze and Shaban, 2022) EEG biomarkers may serve as a more practical and temporally dynamic endpoint compared to fMRI biomarkers. Current efforts to standardize experimental design and analysis of these markers are laudable and may lead to the necessary extensive validation before such markers (neuroimaging or signal-based) can support regulatory approval (Ekhtiari et al., 2022, 2024).

Future designs of randomized controlled studies also need to account for key practical considerations relevant to the care of patients with substance use disorder to ensure the feasibility of these interventions on a larger scale outside of an investigative context. Novel approaches to neurostimulation, including accelerated TMS and LIFU, may help achieve this goal by reducing total intervention time and more directly targeting the reward circuitry underlying craving and addiction. Ongoing refinement of neuromodulatory techniques and advancement in the understanding of neurocircuitry will further improve their efficacy and may transform the treatment landscape for substance use disorders. While the NAc for DBS and focused ultrasound and the DLPFC for non-invasive stimulation techniques have been the predominant targets for addiction treatment, the optimal target for each modality is not fully established and an area of ongoing research (Mehta et al., 2024; Zammit Dimech et al., 2024). Neuromodulation treatment will likely be concentrated in tertiary, academic medical centers at first. Therefore, it will be critical to target outreach to communities with decreased healthcare access.

Author contributions

SH: Conceptualization, Writing – original draft, Writing – review & editing. LQ: Writing – original draft, Writing – review & editing. NH: Writing – original draft, Writing – review & editing. AC: Writing – original draft, Writing – review & editing. CH: Writing – original draft, Writing – review & editing. KS: Writing – original draft, Writing – review & editing.

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Conflict of interest

CH has patents related to sensing and brain stimulation for the treatment of neuropsychiatric disorders (USPTO serial number: 63/170,404 and 63/220,432; international publication number: WO 2022/212891 A1) as well as use of tractography for circuit-based brain stimulation (USPTO serial number: 63/210,472; international publication number: WO 2022/266000). CH is a consultant for Boston Scientific, Abbott, Medtronic, and Insightec and receives honoraria for educational lectures. KS is a consultant for J & J.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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