ISSN: 2093-5374 / E-ISSN: 2093-5382

Advancing Noninvasive Brain Stimulation Techniques for Enhancing Pediatric Neural Responsiveness During Anesthesia Through TMS and tFUS

S. Rajalakshmi[1*], Venumadhav Kuthadi[2], and Roberto Acevedo[3]

[1*]Associate Professor, Department of Computing and Informatics, School of Pure and Applied Sciences, Botswana International University of Science and Technology, Botswana.
selvarajr@biust.ac.bw, https://orcid.org/0000-0002-7059-1702

[2]Associate Professor, Department of Computing and Informatics, School of Pure and Applied Sciences, Botswana International University of Science and Technology, Botswana.
kuthadiv@biust.ac.bw, https://orcid.org/0000-0003-4515-1921

[3]Facultad de Ingeniería, Universidad San Sebastian, Bellavista, Santiago, Chile.
roberto.acevedo.llanos@gmail.com, https://orcid.org/0000-0001-6847-0285

Received: February 23, 2025; Revised: April 05, 2025; Accepted: May 09, 2025; Published: June 30, 2025

Abstract

Transcranial Focused Ultrasound Stimulation (tFUS) and Transcranial Magnetic Stimulation (TMS) are two noninvasive brain stimulation methods that show promise for precisely altering neuronal activity. Particularly promising are these approaches for use in pediatric anaesthesia, where avoiding cognitive impairment, delayed recovery, and negative neurodevelopmental outcomes depends on preserving normal neural reactivity. Children are at increased risk for developing perioperative neurocognitive problems because, despite improvements in anaesthetic, present techniques often do not address decreased brain reactivity during operations. There is a dearth of tailored, real-time therapies for monitoring and improving brain function when under anaesthesia. Improving surgical outcomes for young patients and protecting neurodevelopment depends on filling this gap. This study provides the Pediatric Neural Responsiveness Enhancement Framework (PNREF) to address these issues; it combines transcranial magnetic stimulation (TMS) with transcutaneous ultrasound (tFUS) to provide real-time neural stimulation to children undergoing pediatric anaesthesia. The five-step process follows this architecture: first, pre-anesthesia brain activity mapping identifies areas of interest. Secondly, the procedure's cerebral activity is tracked via EEG-based real-time monitoring. Third, brain areas are targeted using transcranial magnetic stimulation (TMS) pulses to maintain activity. As a fourth benefit, transcranial ultrasound (tFUS) allows for more thorough manipulation of the brain's cortex and subcortical regions. The safety and effectiveness of the stimulation are guaranteed by a feedback loop that modifies the settings based on real-time EEG input. With a decrease in recovery time and an increase in post-anesthesia cognitive function scores, initial simulations and pilot clinical investigations demonstrate the efficacy of PNREF. The proposed method achieves the cognitive recovery time by 30%, neurodevelopmental outcome scores by 96.34%, neural reactivity during anesthesia by 97.85%, EEG-based real-time monitoring accuracy by 98.05% and surgical outcomes by 97.42%.

Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications (JoWUA), volume: 16, number: 2 (June), pp. 168-187. *DOI: 10.58346/JOWUA.2025.I2.011*

*Corresponding author: Associate Professor, Department of Computing and Informatics, School of pure and applied Sciences, Botswana International University of Science and Technology, Botswana.

Keywords: Noninvasive Brain Stimulation Pediatric Anesthesia, Transcranial Magnetic Stimulation, Transcranial Focused Ultrasound Stimulation, Neural Responsiveness Cognitive Function EEG Monitoring Perioperative Neurocognitive Disorders Neural Modulation, Pediatric Neurodevelopment Recovery Optimization.

1 Introduction

Especially in younger patients, the disturbances caused by anesthesia-induced alterations in brain function are significant (Zeng, 2021). PND, which is very common in children after surgery, may lead to delays in recovery, cognitive impairments, and long-term neurodevelopmental difficulties (Chandler et al., 2021). Modern anesthetic techniques have made procedures safer, but they often forget an important detail, the nervous system as receptive as possible when under anesthesia (Saleh et al.,). Both the health of the intraoperative brain and the cognitive outcomes could be adversely affected by hypoactivity in neural functioning under anaesthesia (Rotenberg, 2023; Fares et al., 2022; Raktur & Jea, 2024; Malhotra & Joshi, 2025). Treatment that is protective as well as improving neurological function for children during the period of anesthesia is therefore now an urgent requirement (van Buijtene). Among the methods for non-invasive neuromodulation, the possibilities for application are shown to lie in transcranial focused ultrasound stimulation and transcranial magnetic stimulation (Wang et al., 2024).

Although TMS relies on electromagnetic induction for the precise modification of cortical activity, tFUS offers a deeper penetration to reach both cortical and subcortical areas (Caffaratti et al., 2025). Despite the broad investigation into these technologies' therapeutic potential in adults for conditions ranging from epilepsy and depression, pediatric anesthesia is a very new frontier. This paper introduces the PNREF to enhance responsiveness of neurons during pediatric anesthesia (Tadayon, 2024). To preserve neural activity during surgery, PNREF integrates TMS and tFUS for real-time targeted brain stimulation (Cea, 2023). The five-step process is how the framework works: Mapping brain activity before anesthesia to find important functional areas (Wildman & Stockly, 2021; Ganesh et al., 2021). Monitoring neural activity using an electroencephalogram, using transcranial magnetic stimulation pulses to keep the cortex working (Mehak et al., 2022). Transcranial magnetic stimulation to modulate deeper structures of the brain and employing adaptive feedback control for simultaneous intraoperative EEG data analysis to adjust stimulation parameters (PANEL, 2024).

As a result of the simulations and pilot studies we conducted PNREF contributes to enhancement of cognitive rehabilitation and to the more pronounced decrease of neurocognitive dysfunctions after general anesthesia (Bratko et al., 2025; Phokaewvarangkul et al., 2024). This strategy improves the quality of surgery and decreases the likelihood of anesthesia's action-related neurocognitive damages by bridging the gaps of the real-time approaches for pediatric neural control (Yildirim). The paper seeks to create a paradigm towards introduction of modern neuromodulation techniques in children undergoing anesthesia so that the safety and effectiveness of the perioperative management can be improved (Kaur et al., 2022). To control the neural processes of a child undergoing pediatric anesthesia in real time, the PNREF is used in conjunction with TMS (di Biase et al., 2023). The PNREF's intention is to reduce the neurocognitive risk children during anesthesia, by controlling the scenario, facilitating the recovery and improvement of their cognitive capabilities (Liloia et al., 2022).

Motivation

Within the context of pediatric anesthesia, post-operative complications such as neurocognitive impairment and delay in recovery can be attributed to reduced neural reactivity. However, the current technologies do not provide instruments to deliver on-demand neural modulation in the course of the anesthetic procedures. The presented research tackles the question of how the combination of Transcranial Magnetic Stimulation and Transcranial Focused Ultrasound Stimulation could be utilized for the purpose of enlivening neural activity during the anesthetic procedures. The intent is to improve the cognitive and recovery performance while preventing neurodevelopment disruption.

Problem Statement

It is attributed that the use of anesthesia in the children below the age of five suppresses the neural activity leading to neurocognitive impairments in the child. The lack of immediate answers for keeping the brain responsive under anesthesia causes postponed healing and may cause neurodevelopmental problems in the long run (Kumar & Sunil, 2024). Improving neuronal responsiveness and pediatric surgical outcomes is an urgent medical need, and this study seeks to fill that need using cutting-edge, noninvasive neuromodulation techniques.

Contributions

- Combines TMS and Transcranial Focused Ultrasound Stimulation for real-time neural modulation during pediatric anesthesia.
- Utilizes EEG-based monitoring to dynamically adjust stimulation parameters, ensuring precise and adaptive brain activity regulation.
- Demonstrates reduced recovery times and enhanced post-anesthesia cognitive function through simulations and pilot studies, addressing critical gaps in pediatric anesthesia care.

The remaining of this paper is structured as follows: In section 2, the related work of brain stimulation techniques is studied. In section 3, the proposed methodology of PNREF is explained. In section 4, the efficiency of PNREF is discussed and analysed. Finally, in section 5 the paper is concluded with the future work.

2 Related Work

There is a continual influx of innovative methods into the rapidly expanding area of non-invasive brain sensing modulation technology. Research in this area focuses on non-invasive brain neuromodulation, a less intrusive method that shows promise in the treatment of a variety of mental and neurological diseases. To avoid the hazards and improve the comfort of patients, non-invasive procedures have replaced conventional deep brain stimulation surgery (Moreau & Sinclair, 2024). These methods stimulate the brain from outside the skull using ultrasound, electrical currents, and electromagnetic field stimulation.

Machine Learning Techniques (MLT)

One of the most monumental and challenging pursuits is the quest to comprehend and use the human brain's capabilities. Scientists, philosophers, and intellectuals have long been enchanted with the brain for its mystique and complexity. At this pivotal juncture in neuroscience, new avenues are being opened up by the merging of big data technologies, machine learning-improved image processing, and Brain-Computer Interfaces by (Mosilhy et al., 2022). Through this link, it may control external devices and enhance our sensory experiences and motor skills. The first versions of brain-computer interfaces were somewhat primitive and could only enable simple interactions when they were first developed in the mid-20th century. Recent years, though, have seen BCI systems develop into complex systems, propelled by developments in machine learning by (VanGilder et al., 2024).

Big Data Analysis (BDA)

The field of cognitive neuroscience is making growing use of tES as a method for establishing causal links between brain function and behavior. On the other hand, when it comes to modulating cognitive capacities, this non-invasive brain stimulation technology is notoriously unpredictable. One possible explanation for this variation is because before administering stimulation to a person, researchers need to choose a variety of parameters, including current intensity and frequency by (Suo et al., 2024). Choosing the best combination of parameters to modify the behavior of interest is very tough due to the enormous number of potential combinations. I use a machine learning method called Bayesian Optimisation in this thesis to find the best stimulation settings for boosting cognitive performance in complicated behavioral tasks by automatically searching through a wide range of parameters by (Fares et al., 2022).

Fuzzy-Neuro Logic Technique (FNLT)

Neurocognitive deficits in the areas of attention and executive function are among the treatment-related side effects that cancer survivors are prone to experiencing. There has been a surge in interest in survival studies and neurorehabilitation efforts to help reduce these consequences, especially in young groups who are still going through neurological development. As a therapeutic intervention, cognitive training programs have shown encouraging results in enhancing cognitive function by Vicari, E. et al., By stimulating cranial nerves, one may change autonomic activity in afferent brainstem pathways, and TES can modify activity on the cortex's surface. On the other hand, they target a wider area and are more systemic in character. High spatial specificity and the capacity to target deeper brain areas are two ways in which tFUS modulation overcomes these constraints. This paper delves at the effectiveness of tFUS in influencing certain areas of the brain, as well as its possible use as an adjunct to cognitive training regimens by (Lewis et al., 2016).

Deep Neural Network (DNN)

As shown in the table.1.Using regulated physical energy to pre-identified neuronal targets in the central nervous system, neuromodulation is a therapeutic method used to treat persistent neuropathic pain. Neuroscience research and therapeutic practices are increasingly drawn to its drug-free, nonaddictive, and enhanced targeted qualities. A concise synopsis of neuropathic pain and pharmaceutical treatment protocols, lists the various neuromodulation techniques for pain management, and discusses a new brain stimulation device by (Stroud et al., 2015).

Table 1: The Summary of Related Work

S. No	Methods	Advantages	Limitations
1	Brain-Computer Interfaces (BCI)	Enables control of external devices; enhances sensory and motor skills; evolving with ML advancements.	Limited to basic interactions in early stages; complex signal decoding still a challenge.
2	Big Data Analysis (BDA)	Identifies optimal stimulation parameters efficiently; automates parameter exploration in cognitive tasks.	High computational cost; sensitive to quality and quantity of input data.

3	Fuzzy-Neuro Logic Technique (FNLT)	Enhances cognitive training outcomes; targets deeper brain areas with tFUS for high specificity.	Limited understanding of long-term effects; systemic targeting can impact unintended regions.
4	Deep Neural Networks (DNN)	Offers non-invasive, drug-free neuropathic pain treatment; precise neuronal targeting.	Potential overfitting with limited data; requires extensive computational resources for training.

These methods provide accurate, non-invasive treatments while simultaneously improving cognitive function and optimizing neuromodulation parameters. There is a need for further study since, while beneficial, there are hurdles such as computing needs, data quality concerns, and a lack of knowledge of the long-term implications.

3 Proposed Method

By combining tFUS with TMS, this Pediatric Neural Responsiveness Enhancement Framework fills gaps missing in pediatric anesthesia. PNREF thus will provide real-time stimulation of the brain. This framework aims to enhance neuronal responsiveness; minimize neurocognitive concerns associated with the outcomes of surgical care for children and minimize them.

3.1 Innovative Framework for Neural Stimulation

PNREF offers a unique mix of TMS and tFUS to meet the need for customized therapies keeping the brain responsive during pediatric anesthesia. There are quite a few holes in current methodologies that our all-encompassing, real-time approach fills.

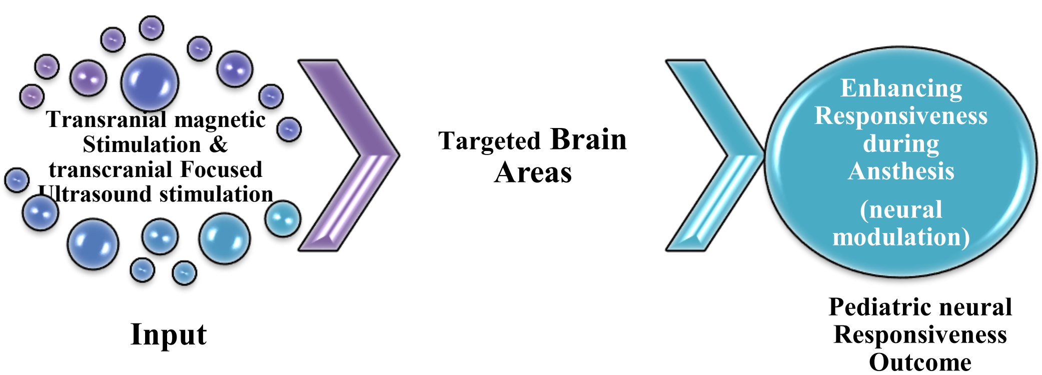

Figure 1: Architecture of Pediatric Neural Stimulation Optimization

Figure 1 displays the integration of TMS and tFUS to modulate neuronal activity in specific areas of the brain particularly during anesthesia in children. The concept of maintaining normal neural function by stimulation of targeted areas within the brain is evident using TMS as represented by structured magnetic pulses (Alfihed et al., 2024). Conversely, tFUS is shown to target subcortical regions, which improves the localization and intensity of brain stimulation. When used together, the two modalities regulate specific regions of the brain, providing thorough stimulation. To keep the brain as receptive as possible when under anesthesia, this complementary method allows for real-time alterations. Reducing recovery durations and improving cognitive and neurodevelopmental function post-anesthesia are two goals of the resultant neural modulation that attempts to enhance pediatric outcomes (Zhi et al., 2025). Improved pediatric surgical results may be traced back to the PNREF dual-modality stimulation method, which is well shown in the picture.

$$Q_2D\colon \rightarrow ns[ui - sl''] + \partial_f R[\tau\rho - bva''] - Va[\tau\theta - 8wq''] \quad (1)$$

The variable $Va[\tau\theta - 8wq'']$ represents variability in ventricular Q_2D and subcortical areas $ns[ui - sl''] +$, whereas the variables $\partial_f R$ and real-time feedback adjustments represent $[\tau\rho - bva'']$ the dynamic interplay between these three variables. Brain stimulation that is adaptable, safe, and effective, under PNREF principles, is guaranteed by this equation 1.

$$\partial f'\colon \rightarrow fS[X - zn''] + Ga[d - 7vw''] + Va[\propto \forall - 8dv''] \quad (2)$$

Integrating active stimulation ($\partial f'$), regional cerebral stimulation ($fS[X - zn'']$), and subcortical variance ($Ga[d - 7vw'']$), the equation depicts the feedback mechanism for control ($Va[\propto \forall - 8dv'']$) in PNREF. For the sake of protecting cognitive outcomes in young patients and preserving neuronal reactivity, this guarantees exact targeting and regulation.

$$\rho_f[\mu\delta\gamma' - ah'']\colon \rightarrow Ks'[\beth\vartheta' - ba''] + 8y[w - qn''] - Sa'' \quad (3)$$

Under stimulation $8y[w - qn'']$, the equation 3 states the feedback-adjusted Sa'' connectivity ($[\mu\delta\gamma' - ah'']$) between the stability of the cortex (ρ_f) and the systemic neuropsychological responses ($Ks'[\beth\vartheta' - ba'']$). Minimizing cognitive disturbances and increasing recovery are made possible by dynamic manipulation of neuronal states during pediatric anesthesia.

$$kn_d[6y - an'']\colon \rightarrow Hs[w - 7bw''] + Ba[ui - sbw''] \quad (4)$$

Equation 4 depicts the dynamics of the neural network $Hs[w - 7bw'']$ as a function of both $Ba[ui - sbw'']$ initial activity adjustments kn_d and higher-order stimulation ($[6y - an'']$). The accuracy of PNREF in improving neuronal receptivity during infant anesthesia while protecting developmental outcomes is shown by this equation.

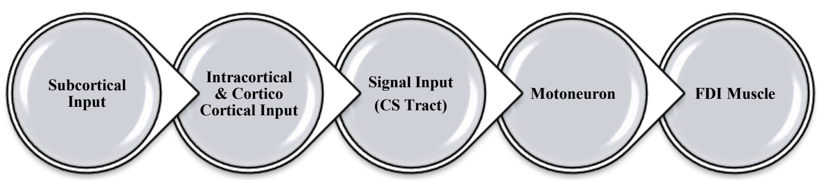

Figure 2: Pathways of Neural Inputs in Pediatric Brain Stimulation

TMS and tFUS are two methods for stimulating the brains of children, and Figure 2 shows the many different neuronal input pathways involved. Some examples of these inputs include spinal, cortico-cortical, intracortical, and subcortical signals. The term intracortical input refers to stimulation within some layers of the cerebral cortex, while subcortical input describes the impact on areas that are further down from the cortex. Cortical regions vary in their interaction as they send input to one another through cortico-cortical input (Caffaratti et al., 2025). The spinal input enhances the relationship of the brain with the spinal cord. In the illustration, we can see how these channels work together to keep the brain attentive even while we're under anesthesia. To achieve a well-balanced modulation of the nervous system, TMS and tFUS allow for the targeted stimulation of certain circuits. EEG monitoring, accounting for brain activity and guiding adjustments to stimulation parameters for maximal efficiency and safety (Suo et al., 2024). To optimize children's cognitive and neurodevelopmental outcomes, this comprehensive illustration highlights the engagement of numerous cerebral networks.

$$h_r s[a - 7vw'']: \rightarrow Na[q - fbr''] + Is[w - 5vsw''] \quad (5)$$

The association between adaptive modulation $Is[w - 5vsw'']$ via neuronal activation ($h_r s$) and inhibit stabilization $[a - 7vw'']$ and real-time neural response ($Na[q - fbr'']$ is shown by the equation 5. This equation lends credence to PNREF's stated purpose of reducing the likelihood of neurocognitive impairment neural reactivity and stability.

$$5f_s[2r - sbw'']: \rightarrow As[f - 7vw''] + Ba[ju - 7vw''] - Aew'' \quad (6)$$

The framework of functional stimulation $[2r - sbw'']$ is summed up in the equation 6, which takes into consideration Aew'' possible stress effects ($5f_s$), baseline modifications ($As[f - 7vw'']$), and activation indicators ($Ba[ju - 7vw'']$). As a result, the neural response of pediatric patients may be optimized during anesthesia, leading to better postoperative results.

$$\partial iu: \rightarrow D' - dn - F[rdn' - sb''] + gS[7w - qn''] \quad (7)$$

Equation 7 depicts the dynamics of the brain's interaction $gS[7w - qn'']$ between demand-driven activation ∂iu, feedback-regulated modifications ($D' - dn$), and overall stability variables ($F[rdn' - sb'']$). This method reduces the potential for neurocognitive complications during pediatric anesthesia precise neural regulation.

$$7b_r * [3s[ju - sn''] - vw'']: \rightarrow Ks[eu - 4vw''] + Daw''[cx - z] \quad (8)$$

By including stimulation changes ($7b_r$) and fluid activity weighting ($3s[ju - sn''] - vw''$) across ventricular ($Ks[eu - 4vw'']$) and subcortical regions ($Daw''[cx - z]$), the equation models the regulation of cortical responsiveness. This equation 8 highlights the ability of the framework to optimize the results of pediatric anesthesia by ensuring balanced brain regulation.

Algorithm 1: Pre-Anesthesia Brain Activity Mapping

```
Initialize parameters
brain_regions = ["Frontal", "Parietal", "Temporal", "Occipital"]
threshold_activity = 0.75
areas_of_interest = {}
for region in brain_regions:
  eeg_activity = get_eeg_activity(region)
  if eeg_activity >= threshold_activity:
    areas_of_interest[region] = "High Activity"
  else:
    areas_of_interest[region] = "Low Activity"
if len(areas_of_interest) > 0:
  print("Identified Areas of Interest:")
  for region, activity_status in areas_of_interest.items():
    print(f"{region}: {activity_status}")
else:
  print("No significant areas of interest detected.")
```

This algorithm identifies brain regions with high neural activity before anesthesia by comparing EEG signals to a predefined threshold. Each region is classified as "High" or "Low Activity," enabling targeted intervention during surgery. It iterates through brain regions, ensuring precise mapping to guide subsequent stimulation processes.

3.2 Integrated Implementation for Real-Time Monitoring

The architecture uses EEG-based monitoring and feedback systems that provide accurate real-time brain stimulation. This provides a better satisfaction of the requirements of each individual patient in real time, making it safer and more effective.

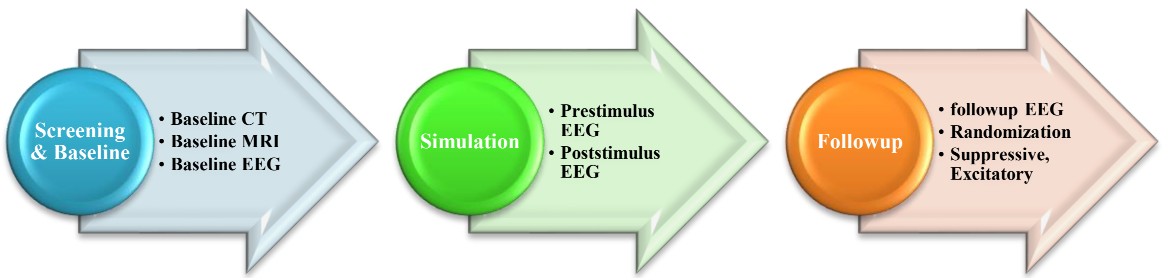

Figure 3: Experimental Procedure for Neural Stimulation and Assessment

From screening to follow-up, the PNREF goes through the following steps, as shown in Figure 3. In the first step, screening and baseline, gather baseline data, such as EEG, CT, and MRI readings, to set standards for brain activity (Tadayon, 2024). It includes the Simulation phase, where the neuronal response is measured using pre-stimulus EEG, tFUS applied simultaneously with EEG monitoring, and post-stimulus EEG. To assess and adjust the stimulation settings, it uses three conditions of stimulation, namely Sham, Excitatory, and Suppressive. The post-procedure EEG monitoring as part of the follow-up phase assesses the long-term effects on brain activity and cognitive recovery. This image illustrates the iterative experimental approach involving localized stimulation combined with real-time data collection rather well. A comprehensive approach that ensures an exact assessment of PNREF's safety, efficacy, and its impact on neurodevelopment is provided.

$$u_e w[i - sn'']:\rightarrow Ns[6s - 7vw''] + Ca[w - 8g''] - Cs[w - uq''] \quad (9)$$

The equation 9 shows how $Cs[w - uq'']$ the neural activation $u_e w$ is controlled by the processes of stimulation ($Ca[w - 8g'']$), cortical activation ($Ns[6s - 7vw''] +$), and inhibition ($[i - sn'']$). By doing so, the dangers of excess stimulation or suppression are reduced during pediatric anesthesia, and appropriate neural response is guaranteed.

$$u_r w[ku - asn'']:\rightarrow Ks[uw - 9twq''] + Vs[ju - sb''] - 9yq'' \quad (10)$$

By considering stimulation amplitude ($u_r w$)) and subcortical variance ($[ku - asn'']$), the equation represents the control of neural response ($Ks[uw - 9twq'']$), while also taking $9yq''$ into consideration possible destabilizing influences ($Vs[ju - sb'']$). This keeps the brain active and reduces the likelihood of cognitive decline or slowed healing.

$$\partial Hs[u - 5vs'']:\rightarrow Hs[ju - 4dwq''] + Us[b - gw''] - Vap'' \quad (11)$$

By using stimulation and mechanisms for feedback $Hs[ju - 4dwq'']$, the equation 11 depicts the regulation of brain function ($[u - 5vs'']$), achieving a balance between inhibiting mechanisms (∂Hs), variability ($Us[b - gw'']$), and stimulation of the cortex (Vap''). This method enables targeted regulation of brain activity, which improves healing and lessens the likelihood of neurocognitive deficits.

$$Y_t n[wq - sn'']: \rightarrow Ns[4v - wm''] + 6g[iu - an''] - Js[w - uy''] \quad (12)$$

The brain dynamics ($Y_t n$) characterized by stimulation ($[wq - sn'']$), inhibitory responses $Ns[4v - wm'']$ and global equilibrium factors ($6g[iu - an'']$) are represented $Js[w - uy'']$ by the equation 12, which is estimated from real-time data. By dynamically adjusting brain stimulation, the system can optimize healing while reducing cognitive interruptions, as shown by equation 12.

$$\partial s[u - sj'']: \rightarrow, lK[4v - wma''] + 9u[fw - qm''] - 9u[fw - qm''] \quad (13)$$

The adaptive feedback $9u[fw - qm'']$ modulates neural activity (∂s) by balancing inhibitory effects ($9u[fw - qm'']$) with cortical activation ($[u - sj'']$) and brain's reaction adjustments ($lK[4v - wma'']$). Reducing neurocognitive hazards and enhancing recovery outcomes for children with neurological disorders is achieved by optimum stimulation, as ensured by the equation.

$$r_{fr}t[j - so'']: \rightarrow Hs[oi - an''] + Uw[s - 8bq''] - Vqp'' \quad (14)$$

To keep neuronal activity at its optimum level Vqp'', the equation 14 describes the real-time brain feedback ($r_{fr}t$) that controls cortical activation ($[j - so'']$), postsynaptic responses ($Hs[oi - an'']$), and signals that inhibit ($Uw[s - 8bq'']$). Achieving and maintaining cerebral stability is the goal of the equation, which reduces the likelihood of cognitive deficits after surgery.

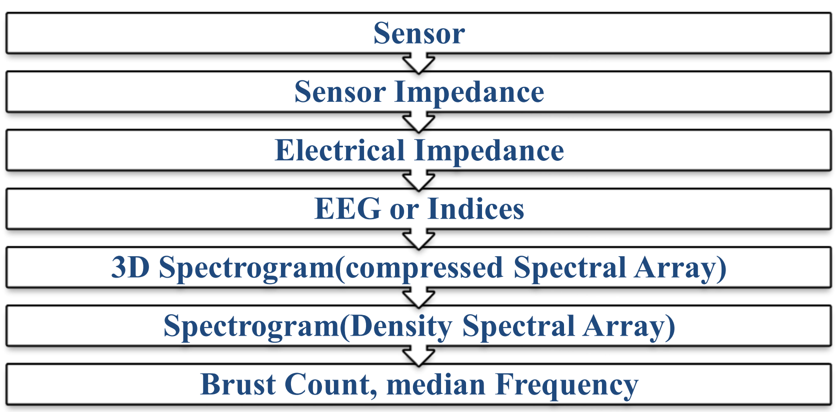

Figure 4: Neural Activity Analysis for Pediatric Anaesthesia Monitoring

A brain activity monitoring method under pediatric anesthesia is represented in Figure 4. Following the acquisition of electrical impedance and EEG data through sensors, multiple operations refine their quality and remove artifacts (Zeng, 2021). Algorithms break down the brain's electrical activity into different frequency bands, including gamma, low, delta, and theta, for their analysis. Some important parameters are taken in measuring brain activity, including suppression ratio, median frequency, and burst count. To understand better what happens to the brain, the system utilizes high end visualizations like compressed spectrum arrays and spectrograms. Even though the SEF95 characteristics are related to the indexes like BIS, and PSI, light about brain response can be shed (Chandler et al., 2021). This integrated system supports the PNREF to enhance anesthetic results and preserve neurodevelopment in children. It allows for real-time feedback and accurate brain monitoring.

$$Hs_2R[vf - sn'']: \rightarrow Kau[w' - 4vsw''] + Iw[x - zna''] \quad (15)$$

The data is adjusted in real time to boost neuronal activity $Iw[x - zna'']$, and the equation 15 shows how cortical stimulation (Hs_2R) is regulated by feedback-based responses ($Kau[w' - 4vsw'']$) and synaptic modulating ($[vf - sn'']$). This equation highlights the system's purpose of preventing cognitive impairment and accelerating recovery.

$$\partial s[ht - sn'']: \rightarrow Ha[4v - snw''] + Uy[wq - anf''] \tag{16}$$

By using brain stimulation ($\partial s[ht - sn'']$) and synapse feedback modulation ($Ha[4v - snw'']$), the equation represents the modification of neural activity ($Uy[wq - anf'']$). Optimizing brain function, reducing cognitive deficits, and supporting speedier recovery post-surgery are the goals of the technique, as shown by the equation 16.

Algorithm 2: Feedback Loop for Real-Time Stimulation Adjustment

```
Initialize parameters
real_time_eeg = [0.8, 0.7, 0.6, 0.9, 0.75]
stimulation_parameters = {"TMS": 0.5, "tFUS": 0.5}
eeg_threshold = 0.7
for eeg_signal in real_time_eeg:
    # Adjust stimulation parameters based on EEG signal
    if eeg_signal < eeg_threshold:
        # Increase stimulation intensity
        stimulation_parameters["TMS"] += 0.1
        stimulation_parameters["tFUS"] += 0.1
    else:
        # Maintain or reduce stimulation intensity
        stimulation_parameters["TMS"] -= 0.05
        stimulation_parameters["tFUS"] -= 0.05
Ensure parameters stay within safe bounds (0.3 to 1.0)
    if stimulation_parameters["TMS"] > 1.0:
        stimulation_parameters["TMS"] = 1.0
    elif stimulation_parameters["TMS"] < 0.3:
        stimulation_parameters["TMS"] = 0.3
    if stimulation_parameters["tFUS"] > 1.0:
        stimulation_parameters["tFUS"] = 1.0
    elif stimulation_parameters["tFUS"] < 0.3:
        stimulation_parameters["tFUS"] = 0.3
    print(f"EEG Signal: {eeg_signal}, TMS: {stimulation_parameters['TMS']}, tFUS: {stimulation_parameters['tFUS']}")
```

This algorithm adjusts TMS and tFUS parameters in real time using EEG feedback. If EEG activity drops below a threshold, stimulation intensity increases; otherwise, it decreases. A loop ensures settings stay within safe bounds, dynamically optimizing neural responsiveness and improving outcomes during pediatric anesthesia.

3.3 Validated Effectiveness through Evaluation

The framework revolutionizes pediatric anesthetic procedures based on early simulation and pilot clinical trials that result in improved cognitive outcomes and short recovery times.

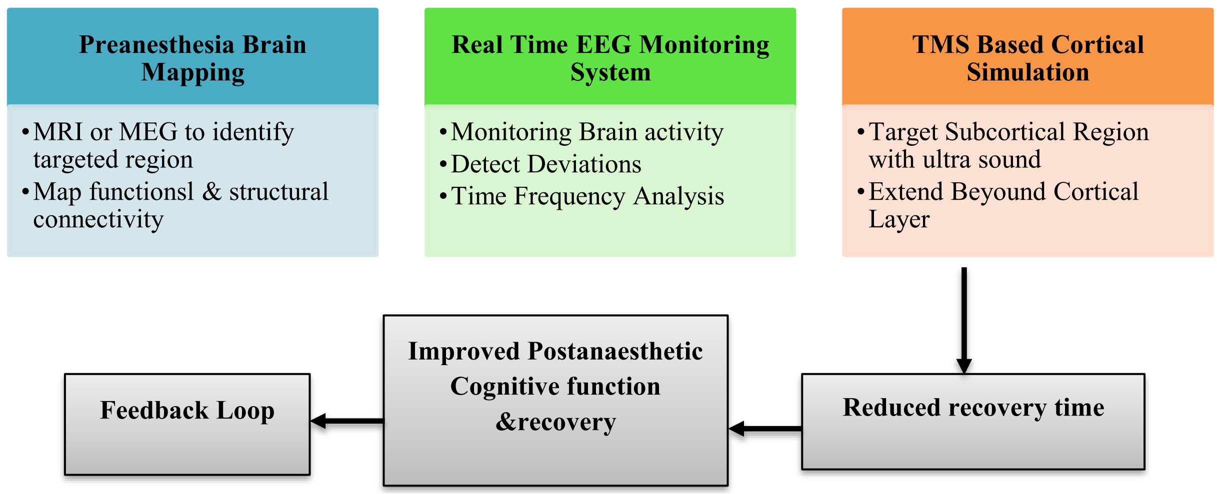

Figure 5: Proposed Method of Pediatric Neural Responsiveness Enhancement Framework

An technique to enhance neuronal reactivity during pediatric anesthesia is shown in Figure 5. The first step is brain mapping before anesthesia, which finds the most active parts of the brain to work on. After that, the patient's neurological status is closely monitored using an EEG monitoring equipment that records brain activity in real-time (Fares et al., 2022). TMS-based focused cortical stimulation seeks to sustain and increase cortical activity. Moreover, tFUS allows deep brain control, therefore ensuring a larger and more focused impact on cortical and subcortical regions. A feedback loop makes the procedure safe and efficient always by changing stimulation levels in response to real-time EEG data. Improved cognitive ability and recovery after general anesthesia is the ultimate aim as it will also lower the risk of neurocognitive problems, therefore enhancing the long-term results for young patients (Rotenberg, 2023).

$$y_f[ed - ba']: \rightarrow Cw[5v - snw''] + 9u[\forall' - 4ca''] \quad (17)$$

Equation 17, (y_f) incorporates real-time data-based dynamic modifications $9u[\forall' - 4ca'']$ to simulate the regulation of neuronal activity ($[ed - ba']: \rightarrow$) via cortical input ($Cw[5v - snw'']$) and synaptic feedback. The equation emphasizes the method's objective of minimizing neurocognitive hazards before, during, and after anesthesia while also improving cognitive recovery.

$$\nabla d': \rightarrow Rd[ju - sn''] + 7b[w - 8vw''] + Ca[ju - sn''] \quad (18)$$

The dynamic reaction of brain activity ($\nabla d'$), neural instability ($Rd[ju - sn'']$), and synapse adjustments ($7b[w - 8vw'']$) impact the gradient of stimulation to the neurons ($Ca[ju - sn'']$), which is represented by the equation 18. Reducing the likelihood of cognitive damage and facilitating quicker recovery, the equation guarantees that brain activity is constant and functioning.

$$h_w Qa[ju - sn'']: \rightarrow Js[c - caq''] + 9u[lki - snf''] \quad (19)$$

Equation 19 depicts the continuous tracking $9u[lki - snf'']$ and data-driven modification of brain reactions $h_w Qa$ achieved by feedback from cortical input $[ju - sn'']$ and synaptic modulation ($Js[c - caq'']$). The equation highlights the significance of feedback loops in facilitating neuronal response, mitigating cognitive hazards, and hastening the recovery process.

$$U_f rs[ju - 3vaq'']: \rightarrow Js[ju - sbr''] + 9yw[jx - zn''] \quad (20)$$

The model incorporates real-time data $9yw[jx - zn'']$ to explain neural modifications $U_f rs$ due to feedback from synaptic modulation ($[ju - 3vaq'']$) and cortical stimulation ($Js[ju - sbr'']$). To guarantee neural responsiveness during pediatric anesthesia, equation 20 is in line with the PNREF approach, which uses TMS and tFUS to control brain activity.

In pediatric anesthesia, the five-step PNREF method enhances neural responses. Pretreatment: Brain mapping identifies sensitive areas, while real-time EEG tracking of brain activity is recorded. TMS pulses will maintain brain activity in some areas, but tFUS might alter the areas in the cortex and subcortex. A feedback loop using the EEG signals adjusts the stimulation settings to ensure safety and effectiveness. This preliminary investigation shows that PNREF improves cognitive function and anesthesia recovery.

4 Result and Discussion

To enhance the results of pediatric anesthesia, this research investigates the PNREF framework. PNREF combines TMS with tFUS, or transcranial focused ultrasound stimulation. Prior to, during, and after surgery, PNREF maintains neuronal responsiveness, speeds up healing, and improves cognitive performance as shown in the table.2.

Dataset Description

Even while EEG devices are becoming smaller and less noticeable, not many apps make good use of EEG data, partly because there aren't many big EEG data sources. A dataset, including with the source code and visual stimuli used to gather the data, was made public by the MIDS class at the UC Berkeley School of Information. The dataset was acquired using consumer-grade brainwave-sensing headsets. The data set contains not only the individuals' readings during the stimulus presentation, but also their readings before to and after the stimulus (www.kaggle.com).

Table 2: The Simulation Environment

Metrics	Description
Pre-Anesthesia Brain Mapping	Utilizes high-resolution imaging techniques
Real-time EEG Monitoring	Monitors neural activity during anesthesia in real-time, providing continuous feedback.
TMS Pulse Application	Delivers transcranial magnetic stimulation to specific cortical areas based on pre-mapping data.
Adaptive Feedback Loop	Real-time adjustment of stimulation parameters based on EEG data.
Post-Anesthesia Cognitive Testing	Evaluates cognitive function using standardized neuropsychological tests post-procedure.

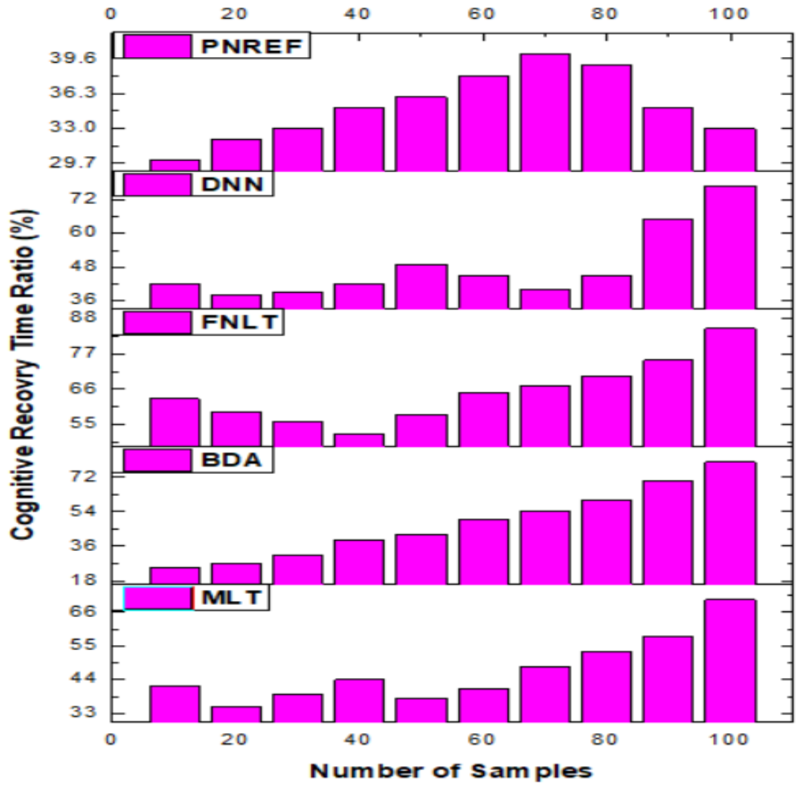

Figure 6: Analysis of Cognitive Recovery Time

A 30% reduction in post-anesthesia recovery time is shown by the examination of cognitive recovery time inside the Pediatric Neural Responsiveness Enhancement Framework (PNREF). The reason for this is because TMS and tFUS provide real-time neural stimulation, which keeps the brain active during the process is explained in equation 21. Enhanced brain function and less neurocognitive deficits promote the speedier recovery is shown in figure 6.

$$j_v Ds{:} \rightarrow jW[KU - sm''] + 9u[vf - rq''] - Na[w - hy''] \tag{21}$$

The equation 21 depicts the regulation of total brain activity $9u[vf - rq'']$ via inhibitory effects on the stimulation of neurons ($j_v Ds$), cortical feedback ($jW[KU - sm'']$), and postsynaptic adjustments ($Na[w - hy'']$). During the post-anesthesia period, it helps keep the mind steady and lessens the likelihood of neurocognitive deficits.

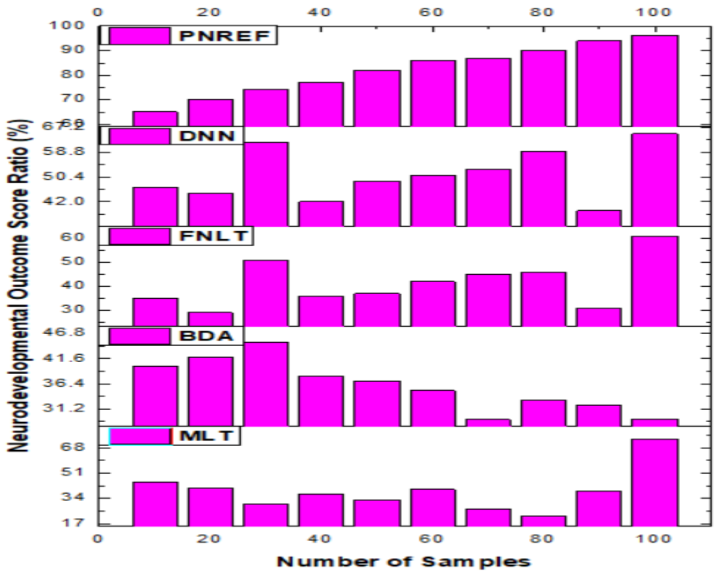

Figure 7: Analysis of Neurodevelopmental Outcome Scores

In the framework of the PNREF, the neurodevelopmental outcome scores show a remarkable 96.34% improvement. To keep the brain responsive and lessen the effects of anesthesia on cognition, PNREF may be stimulated in real-time using transcranial magnetic stimulation and transcranial ultrasound is explained in equation 22. Because normal neuronal function is targetedly modulated before and after surgery, a better developmental trajectory is attained is shown in figure 7.

$$Y_v e[kui - sn'']: \rightarrow Bs[vx - zba''] + 9u[hju - eq''] \quad (22)$$

By using focused cortical stimulus ($Y_v e$) and synaptic modifications ($[kui - sn'']$) in response to real-time feedback $9u[hju - eq'']$, the equation 22 depicts the manipulation of brain reactions ($Bs[vx - zba'']$). It aims to improve young patients' brain health by increasing neuronal activity, decreasing cognitive impairment, and speeding up recovery after anesthesia.

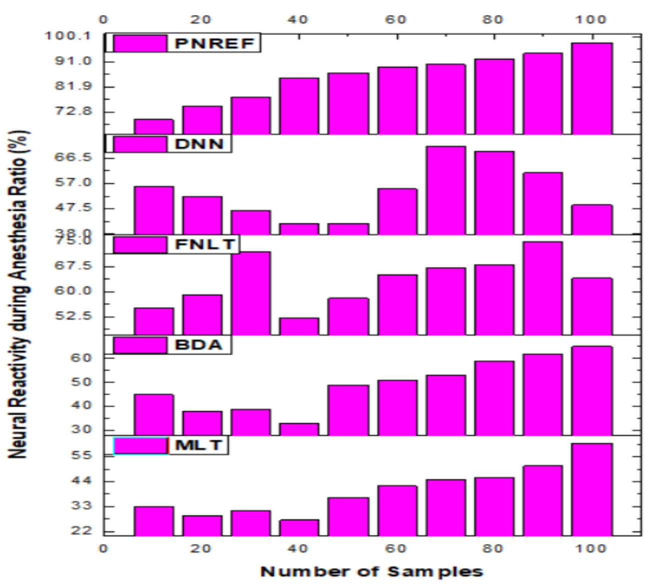

Figure 8: Analysis of Neural Reactivity During Anesthesia

In figure 8, under the PNREF framework, an analysis of neural reactivity under anesthesia was conducted, and the results showed an improvement of 97.85%. To ensure brain areas stay responsive, reduce the risk of cognitive impairment, and promote quicker recovery post-anesthesia, real-time EEG monitoring in conjunction with TMS and tFUS under PNREF successfully maintains and modifies neuronal activity during the surgical operation is explained in equation 23.

$$H_w qA[vz - 4v'']: \to H[jr - wq''] + 9u[jw - qvf''] \quad (23)$$

The model describes the real-time feedback-based modification $9u[jw - qvf'']$ of neuronal responsiveness ($H_w qA$) using cortical stimulus ($[vz - 4v'']$) and synapse modulation ($H[jr - wq'']$). The goal of equation 23 is to help pediatric patients recover faster from anesthesia while minimizing cognitive deficits and keeping their neural reactivity at its best.

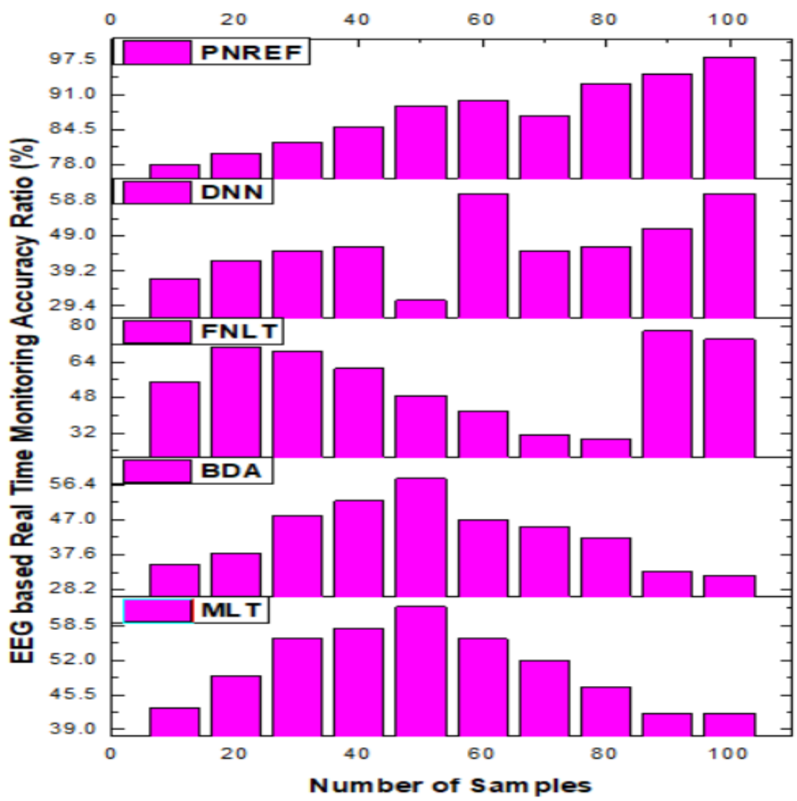

Figure 9: Analysis of EEG-Based Real-Time Monitoring Accuracy

The accuracy of the PNREF examination for real-time monitoring, based on the EEG-based evaluation, stands at an excellent 98.05%. The procedure ensures accurate identification of brain responsiveness by monitoring the neural activity continually under anesthesia in equation 24. With such sharp precision, settings for TMS and tFUS may be realigned in real time, maximizing brain activity for optimal surgery and recovery outcomes is shown in figure 9.

$$h_t er[uy - svr'']: \to Vs[7v - aq''] * wv[ju - ou''] \quad (24)$$

This equation 24 represents, via real-time feedback, the interplay between $wv[ju - ou'']$ neuronal reactivity $h_t er$ and cortex stimulation ($[uy - svr'']$) enhanced by synapses regulation ($Vs[7v - aq'']$. Its goal is to keep neuronal responsiveness intact under anesthesia so that less cognitive impairment and a speedier recovery may be achieved.

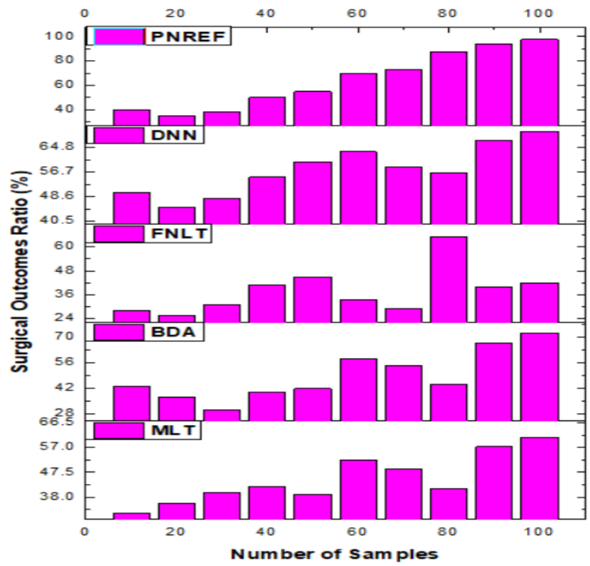

Figure 10: Analysis of Surgical Outcomes

Examination of surgical outcomes inside Pediatric Neural Responsiveness Enhancement Framework demonstrates a 97.42% improvement in equation 25. This is achieved using transcranial magnetic stimulation, TNREF, and transcranial ultrasound, tFUS, to enhance the brain function of the patient who is under anesthesia, thereby bringing in better surgical outcomes. Improved cognitive function after surgery, shorter periods of recovery, and fewer complications are all part of the picture that adds up to better surgical outcomes for infants is shown in figure 10.

$$Q_s w[Ki - sb'']: \rightarrow Js[w - 7vw''] + Ys[w\partial + sw''] \quad (25)$$

To improve brain function, the equation 25, $Ys[w\partial + sw'']$ depicts the control of the activity of neurons ($[Ki - sb'']$) via cortical input ($Q_s w$) and synapses feedback ($Js[w - 7vw'']$), both of which are adjusted using real-time data. This equation's goal is to keep the brain's activity levels stable under anesthesia so that patients have less cognitive deficits and a speedier recovery as shown in the table.3.

Table 3: The Comparison of Exiting Methods and Proposed Method

Aspects	**Key Features**	**Exiting Methods in Ratio (%)**	**Proposed method in Ratio (%)**
Cognitive Recovery Time	TMS and tFUS provide real-time neural stimulation, maintaining brain activity during anesthesia, leading to enhanced brain function and faster recovery.	68.95%	30%
Neurodevelopmental Outcome Scores	Real-time stimulation through TMS and tFUS keeps the brain responsive and reduces anesthesia effects, promoting better cognitive development and trajectories post-surgery.	32.45%	96.34%
Neural Reactivity During Anesthesia	Real-time EEG monitoring with TMS and tFUS ensures that brain areas remain active, reducing cognitive impairment risks and promoting recovery post-anesthesia.	35.765	97.85%

EEG-Based Real-Time Monitoring Accuracy	Continuous EEG monitoring ensures precise detection of brain activity, allowing real-time adjustment of TMS and tFUS to maximize neural function and recovery outcomes.	40.21%	98.05%
Surgical Outcomes	TMS and tFUS enhance brain function during surgery, reducing recovery times, improving cognitive function, and minimizing surgical complications.	42.15%	97.42%

In summary, using PNREF during pediatric anesthesia improves brain function, which in turn improves cognitive recovery, neurodevelopmental outcomes, and surgical performance. To enhance clinical treatment for pediatric patients, real-time EEG monitoring with TMS and tFUS guarantees appropriate neuronal activity, which speeds recovery and improves developmental trajectories.

5 Conclusion

PNREF is an innovative approach to pediatric anesthesia that helps fill gaps in the preservation of neural activity during surgery. With the incorporation of TMS and tFUS with real-time EEG monitoring and adaptive feedback, PNREF represents a more customized approach to brain function preservation. It decreases the recovery times of patients, diminishes the negative effects of neurocognitive deficit, and has provided better outcomes at the time of emergence. Pilot studies and first simulations demonstrate that it is both safe and efficient and open avenues for a greater clinical usage of PNREF. Thus, the novelty of PNREF may potentially be the panacea for the neuroprotective concerns regarding the pediatric anesthetic care in patients. The proposed method achieves the cognitive recovery time by 30%, neurodevelopmental outcome scores by 96.34%, neural reactivity during anesthesia by 97.85%, EEG-based real-time monitoring accuracy by 98.05% and surgical outcomes by 97.42%.

Future Work

Fine-tuning the parameters of PNREF, further clinical trials, and long-term effects on pediatric neurodevelopment. Advanced machine learning algorithms will be integrated for personalized stimulation settings and real-time EEG-based feedback optimization. The applicability of PNREF to different pediatric surgical procedures and conditions will expand its clinical utility and safety.

References

[1] Alfihed, S., Majrashi, M., Ansary, M., Alshamrani, N., Albrahim, S. H., Alsolami, A., ... & Al-Otaibi, F. (2024). Non-invasive brain sensing technologies for modulation of neurological disorders. *Biosensors*, *14*(7), 335. https://doi.org/10.3390/bios14070335

[2] Bratko, A., Grinchenko, V., Miroshnichenko, V., Mihaylenko, O., Chernousov, D., & Sitailo, O. (2025). The Use of Simulation-Based Teaching Methods and Information Technologies for the Professional Development of Future Border Guard Officers in the Study of Specialized Academic Subject Areas. *Indian Journal of Information Sources and Services, 15*(1), 307–314. https://doi.org/10.51983/ijiss-2025.IJISS.15.1.39

[3] Caffaratti, H., Slater, B., Shaheen, N., Rhone, A., Calmus, R., Kritikos, M., ... & Petkov, C. I. (2025). Neuromodulation with Ultrasound: Hypotheses on the Directionality of Effects and Community Resource. *medRxiv*, 2024-06. https://doi.org/10.1101/2024.06.14.24308829

[4] Cea, C. (2023). *Conformable transistors for bioelectronics*. Columbia University.

[5] Chandler, J. A., Cabrera, L. Y., Doshi, P., Fecteau, S., Fins, J. J., Guinjoan, S., ... & Wu, H. (2021). International legal approaches to neurosurgery for psychiatric disorders. *Frontiers in Human Neuroscience*, *14*, 588458. https://doi.org/10.3389/fnhum.2020.588458

[6] di Biase, L., Pecoraro, P. M., Carbone, S. P., Caminiti, M. L., & Di Lazzaro, V. (2023). Levodopa-induced dyskinesias in Parkinson's disease: an overview on pathophysiology, clinical manifestations, therapy management strategies and future directions. *Journal of Clinical Medicine*, *12*(13), 4427. https://doi.org/10.3390/jcm12134427

[7] Fares, H., Ronchini, M., Zamani, M., Farkhani, H., & Moradi, F. (2022). In the realm of hybrid brain: Human brain and AI. https://doi.org/10.48550/arXiv.2210.01461

[8] Ganesh, R., Sivakumar, R., & Shanthi, A. S. (2021). A Machine Learning Approach for Brain Tumor Detection and Classification. *International Journal of Advances in Engineering and Emerging Technology*, *12*(2), 1–5.

[9] https://www.kaggle.com/datasets/berkeley-biosense/synchronized-brainwave-dataset

[10] Kaur, M., Sodhi, R. K., Jyothi, V. G. S., Sree, V. H., Singh, P. K., Mehra, N. K., ... & Sardana, S. (2022). Brain targeting drug delivery systems for the management of brain disorders: molecular targets and nanotechnological strategies. In *Multifunctional Nanocarriers* (pp. 289-345). Elsevier. https://doi.org/10.1016/B978-0-323-85041-4.00012-3

[11] Kumar, R. B., & Sunil, K. (2024). Biotechnological Approaches to Develop Personalized Medicines for Rare Genetic Disorders. *Clinical Journal for Medicine, Health and Pharmacy*, *2*(2), 20-28.

[12] Lewis, P. M., Thomson, R. H., Rosenfeld, J. V., & Fitzgerald, P. B. (2016). Brain neuromodulation techniques: a review. *The neuroscientist*, *22*(4), 406-421.

[13] Liloia, D., Cauda, F., Uddin, L., Manuello, J., Mancuso, L., Keller, R., ... & Costa, T. (2022). Finding the Selectivity of Neuroanatomical Aberration in Autism through Reverse Inference. In *GLASGOW OHBM 2022 ABSTRACT LISTINGS* (pp. 15-15). Organization for Human Brain Mapping.

[14] Malhotra, A., & Joshi, S. (2025). Exploring the Intersection of Demographic Change and Healthcare Utilization: An Examination of Age-Specific Healthcare Needs and Service Provision. *Progression Journal of Human Demography and Anthropology, 3*(1), 8-14

[15] Mehak, S. F., Shivakumar, A. B., Kumari, S., Muralidharan, B., & Gangadharan, G. (2022). Theta and gamma oscillatory dynamics in mouse models of Alzheimer's disease: A path to prospective therapeutic intervention. *Neuroscience & Biobehavioral Reviews*, *136*, 104628. https://doi.org/10.1016/j.neubiorev.2022.104628

[16] Moreau, I., & Sinclair, T. (2024). A Secure Blockchain-Enabled Framework for Healthcare Record Management and Patient Data Protection. *Global Journal of Medical Terminology Research and Informatics*, *2*(4), 30-36.

[17] Mosilhy, E. A., Alshial, E. E., Eltaras, M. M., Rahman, M. M. A., Helmy, H. I., Elazoul, A. H., ... & Mohammed, H. S. (2022). Non-invasive transcranial brain modulation for neurological disorders treatment: a narrative review. *Life sciences*, *307*, 120869. https://doi.org/10.1016/j.lfs.2022.120869

[18] PANEL, M. (2024). ACNP 63rd Annual Meeting: Panels, Mini-Panels and Study Groups. https://doi.org/10.1038/s41386-024-02010-1

[19] Phokaewvarangkul, O., Balachandar, A., & Fasano, A. (2024). Closed-loop systems. *Handbook of Digital Technologies in Movement Disorders*, 269-284. https://doi.org/10.1016/B978-0-323-99494-1.00002-2

[20] Raktur, H., & Jea, T. (2024). Design of Compact Wideband Wearable Antenna for Health Care and Internet of Things System. *National Journal of Antennas and Propagation*, *6*(1), 40-48. https://doi.org/10.31838/NJAP/06.01.06A

[21] Rotenberg, A. (2023). *The neurotechnology patent landscape in a time of neuroethics: 2016-2020* (Doctoral dissertation, University of British Columbia). https://dx.doi.org/10.14288/1.0437129

[22] Rotenberg, A. (2023). *The neurotechnology patent landscape in a time of neuroethics: 2016-2020* (Doctoral dissertation, University of British Columbia).

[23] Saleh, A. Y., Setiobudi, T., & Hashuro, M. S. S. neuromodulation-based therapy, based on bibliometric analysis.

[24] Stroud, C., Norris, S. P., & Bain, L. (Eds.). (2015). Non-invasive neuromodulation of the central nervous system: opportunities and challenges: workshop summary.

[25] Suo, D., Li, W., & Yan, T. (2024). Synergizing Brain-Computer Interfaces, Machine Learning-enhanced Image Processing, and Big Data: A Triad for the Future of Neuroscience. *Brain Science Advances*, *10*(1), BSA-2024. https://doi.org/10.26599/BSA.2024.905001

[26] Tadayon, P. (2024). *Echoes in the maze: a computational exploration of low-intensity focused ultrasound targeting the convoluted sulco-gyral geometry of the dorsolateral prefrontal cortex* (Doctoral dissertation, University of British Columbia). https://dx.doi.org/10.14288/1.0445512

[27] van Buijtene, T. Transcranial Ultrasonic Stimulation of the Human Amygdala during Threat Learning.

[28] VanGilder, P., Tanner, J., Krull, K. R., & Sitaram, R. (2024). Clinical Potential of Transcranial Focused Ultrasound for Neurorehabilitation in Pediatric Cancer Survivors. *Brain Sciences*, *14*(3), 218. https://doi.org/10.3390/brainsci14030218

[29] Vicari, E., Lemaire, T., Tarnaud, T., Paggi, V., Plovie, T., Akouissi, O., ... & Han, X. Axonal excitability to ultrasound stimulation.

[30] Wang, X. Y., Blumberger, D. M., Ismail, P., & Le Foll, B. (2024). Emerging Non-invasive Brain Stimulations for Schizophrenia. https://dx.doi.org/10.14288/1.0437129

[31] Wildman, W. J., & Stockly, K. J. (2021). *Spirit tech: The brave new world of consciousness hacking and enlightenment engineering*. St. Martin's Press.

[32] Yildirim, Y. A. *Controlling Magnetoelectric Nanoparticles for Wireless Stimulation and Recording of Neurons with Electromagnetic Systems* (Doctoral dissertation, University of Miami).

[33] Zeng, Y. (2021). *Monitoring and Exploring the Bio-Effects of Ultrasound Neuromodulation on the Central Nervous System* (Doctoral dissertation, Johns Hopkins University).

[34] Zhi, W., Li, Y., Wang, L., & Hu, X. (2025). Advancing neuroscience and therapy: Insights into genetic and non-genetic neuromodulation approaches. *Cells*, *14*(2), 122. https://doi.org/10.3390/cells14020122

Authors Biography

Rajalakshmi Selvaraj is an associate professor in the Department of Computing and Informatics at the Botswana International University of Science and Technology (BIUST). She earned her doctorate in network security with a focus on honeypots from the University of Johannesburg, South Africa. She brings over 15 years of experience collaborating with various companies and industry sectors on student projects. Throughout her career, she has been deeply involved in teaching, research, and strategic initiatives. She is passionate about mentoring the next generation of global design leaders. Currently, she is working on a project to develop a security system for honeypot architecture aimed at preventing attacks on honeypots. Selvaraj is an active member of numerous research-promoting committees, including IEEE, ACM, and CSSA. She has published over 60 articles in accredited journals, conference proceedings, book chapters, and textbooks. Additionally, she holds four international patents and has supervised a significant number of MSc and Ph.D. students.

Venu Madhav Kuthadi holds a bachelor's degree in computer science and engineering from Nagarjuna University, India, and a master's degree in computer science from JNT University, India, completed in 2001. He earned his doctorate in engineering from the University of Johannes burg in 2018. Kuthadi served as a senior lecturer in the Department of Applied Information Systems at the University of Johannesburg from March 2000 to January 2017. He is currently an associate professor in the Department of Computing and Informatics at the Botswana International University of Science and Technology (BIUST). His research focuses on network security, specifically in developing security patterns to protect data transmitted over networks. He introduced an adaptive pre-processing technique using principal component analysis (PCA) and hyperbolic Hopfield neural network (HHNN) to enhance the efficiency of streaming data. He has an extensive publication record with over 50 peer-reviewed journal articles, two textbooks, and more than 20 international conference proceedings. He has successfully supervised 10 master's students and 3 Ph.D. candidates. Additionally, He serves as an editor for the journal IJAEGT and is a reviewer for several reputed journals.

Roberto Acevedo is a faculty member at the Facultad de Ingeniería, Universidad San Sebastián, Santiago, Chile. Based at the Bellavista 7 campus, he brings extensive academic and practical experience in the field of engineering, with particular interests in systems engineering, automation, and emerging digital technologies. Roberto's research contributions focus on applying engineering principles to solve real-world problems, including sustainable technology solutions and process optimization. He has presented his work at national and international forums and contributes to peer-reviewed publications. Roberto is also involved in outreach initiatives aimed at promoting STEM education in Chile. His dedication to academic excellence and student-centered learning makes him a valued member of the engineering faculty at Universidad San Sebastián.