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The current clinical applications of invasive brain-computer interfaces

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Abstract. Brain-computer interface (BCI) technology is an emerging and swiftly expanding advanced technology. It links the brain to external devices, creates a brain-computer interface connection pathway, and ultimately realises information exchange and control. Meanwhile, as modern medicine continues to explore the composition and operation of the brain, the clinical applications of BCI have become more widespread. In particular, in the diagnosis, screening, treatment, and rehabilitation of neurological diseases and motor impairments, BCI is becoming more and more significant. This paper first explains the implementation and present state of BCI and provides a systematic evaluation of invasive BCIs, including the concepts of current invasive treatment techniques. The paper then review the current clinical applications of invasive BCIs technology, discuss its technical applications and benefits through case studies, and provide a comprehensive assessment of its risks. The prospects of invasive BCIs and their growing trend in the medical field are also reviewed.

Keywords: Brain-Computer Interface, Invasive, Neurology, Signal Processing, DBS.

1. Introduction

Brain-computer interface (BCI) technology is a sophisticated communication tool that allows users to communicate with other devices that have computational capabilities. BCI technology can be classified as non-invasive and invasive. Current non-invasive BCIs extract the user's intention from scalp electroencephalographic (EEG) activity. They can help those with severe impairments with basic communication and control [1]. However, non-invasive BCIs cannot provide patients with the ability to manipulate a robotic arm or neuroprosthesis in real-time in multiple dimensions. As research into the structure and function of the brain continues to progress, invasive BCIs are popular in current research to address these limitations but face significant technical difficulties and clinical risks.

A large number of clinical applications based on non-invasive BCIs are being realised. Influenced by the information age, EEG recording and analysis techniques have reached an extremely high level of sophistication. Invasive BCIs are still under development, and there is a lack of reviews on their clinical management. This paper aims to analyse current technological innovations in BCI for clinical neurological disorders and motor disabilities through case studies, leading to a systematic summary of current applications of invasive BCIs for clinical therapies. On the other hand, the risks and challenges of invasive BCIs are also discussed. Finally, the paper provides an outlook on the future of invasive

BCIs for a wider range of clinical applications and guidelines for future research directions in invasive BCIs in the medical and other fields.

2. The Framework of current therapies using invasive BCIs

Invasive BCIs are currently experiencing rapid growth. Researchers can track the activity of each neuron by implanting invasive BCIs into the cortex [2]. Because they are surgically inserted into the brain, invasive BCIs are by far the most accurate. By collecting electrical signals, decoding and noise reduction of the signals, we are able to evaluate and control the precise electrical signals. Compared to non-invasive BCIs, invasive BCIs can obtain neural signals with a substantially greater signal-to-noise ratio (SNR), much higher spatial and temporal resolution, which means they are more robust to electrical noise interference or motion artefacts [3]. Microelectrode Array (MEA), Electrocorticography (ECoG) and Deep Brain Stimulation (DBS) are the most widely employed techniques for invasive BCIs.

2.1. Deep Brain Stimulation (DBS)

Hassler and colleagues pioneered the application of high-frequency, pulsatile stimulation in the treatment of brain disorders in humans in the 1950s [4]. Conventionally, DBS consists of an electrode and a pulse generator. An electrode lead is surgically implanted during DBS therapy into a brain nucleus or fiber tract. An implantable pulse generator (IPG) with a battery and stimulation hardware is subcutaneously placed in the patient's chest. To link the IPG to the DBS line, an extension cable is tunneled beneath the skin, as we can see in figure 1 [5]. DBS involves passing an electric current into tiny areas of brain tissue in order to modify the extracellular potential of cells and fibers around the stimulated electrode. DBS is currently a popular treatment option for neurological conditions like essential tremor, Parkinson's disease, and some kinds of epilepsy.

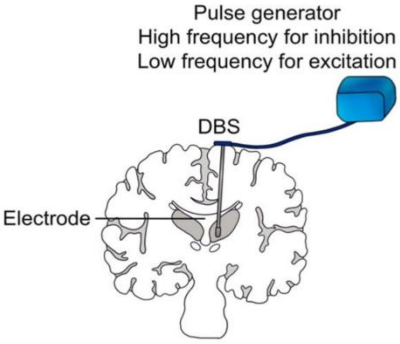

Figure 1. Framework and clinical application of DBS.

2.2. Microelectrode arrays (MEAs)

MEAs are devices containing multiple microelectrodes through which neural signals are acquired or transmitted, acting as a neural interface that connects neurons to electronic circuits. Implantable MEAs are most commonly used in brain-computer interfaces and can be classified into microwire, silicon-based and flexible MEAs. In recent decades, implantable MEAs have been used to drive BCIs in many human and non-human primate experiments [6]. MEAs can record electrocorticogram (ECoG) signals, which can simultaneously record the precise timing and waveforms of neuronal action potentials over a wide range and with high precision, providing a solid foundation for fully extracting neural information and interpreting the activity of neural networks in the brain. On the other hand, by writing information to neurons with high spatial and temporal precision, the MEAs can not only directly transmit new information to the brain, but also modify the abnormal neural network activity of patients with neurological disorders, thus alleviating the symptoms or treating the diseases.

3. Invasive BCI for Clinical Neurological Disorders

Neuromodulation is a promptly developing field of study that encompasses both invasive and non-invasive technological techniques to the treatment of neurological illnesses. For some typical neurological disorders, a significant number of clinical neuromodulation approaches based on BCIs are already available. Neuromodulation therapies show great promise in the treatment of neurological and neurological disorders that cannot be effectively treated by conventional medications.

3.1. Epilepsy

Epilepsy is a common brain diseases characterized by aberrant firing of nerve cells in the brain on an intermittent basis. Of the approximately 50 million people with epilepsy worldwide, as many as 1/3 of patients experience seizures that cannot be managed by anticonvulsants [7]. Invasive BCIs are widely used to detect precursors and dynamic mechanisms of impending seizures and to allow implantable devices to intervene early in the treatment of epilepsy.

In 1984, Wyler and his team placed subdural strip electrodes to record extensively over the cortex. They tracked the electrocorticograms of 28 patients for up to three weeks with just two mild problems, giving a beneficial alternative to inserting intracortical depth electrodes to locate the epileptogenic center [8]. The Neuropace Responsive Neurostimulator is a closed-loop device implanted in the brain that administers DBS pulses when an epileptic seizure is detected. When stimulation is activated, current-controlled biphasic pulses with widths ranging from 40 to 1000 seconds are supplied to 8 electrodes implanted in the brain [9]. Xie designed an ECoG system for wireless brain-cell phone interaction in 2017, which obtains electrical data of brain activity through a high-resolution 32-channel flexible ECoG electrode array, detect electrical signals in the brain in real time, and stimulate the lesions during seizures [10]. The system can be used to treat epileptic seizures by stimulating the lesions in the brain.

The present development of invasive BCIs for the treatment of epilepsy is aimed at improving the material and morphology of the implanted electrodes and creating a closed-loop, rapid-feedback system through the optimisation of algorithms for analysing electrical signals and machine learning.

3.2. Neurodegenerative Disease

Neurodegenerative diseases can, over time, damage and destroy parts of the nervous system, particularly the brain, and the most typical of these is Parkinson's disease (PD). For patients with moderate and advanced PD, medications do not have the desired therapeutic effect, and invasive BCIs are also popular in this field to study their causative factors and seizure control.

The hallmark of PD disease is progressive degradation of midbrain dopaminergic neurons in the substantia nigra [11]. In 1987, Benabid and his team first developed deep brain stimulation (DBS) for thalamic ventral intermediate nucleus tremor [12]. Subsequently, with ongoing research into brain structure and the causes of PD, DBS therapy is now most commonly targeted at the subthalamic nucleus. According to Limousin et al., who placed electrodes bilaterally in the subthalamic nucleus under stereotactic guidance with imaging and electrophysiological testing of the area, these patients' scores on the motor examination and activities of daily living improved [13]. This suggests that this procedure may be useful for treating advanced PD. The difficulty in making a breakthrough in the treatment of PD with DBS lies in the complications of intraoperative infections and immune reactions during the implantation of the electrodes.

3.3. Mental Disorder

A mental disorder is narrowly defined as the existence of a structural or biochemical organic dysfunction of the brain that can result in psychological and behavioral problems of varied degrees of severity. As the study of DBS continues to deepen, DBS is not only able to be utilized to treat disorders of movement, but is also showing results in the area of mental disorders. Mayberg and her team showed that high-frequency DBS at Cg25WM produced significant behavioural changes in six patients with treatment-resistant depression (TRD), and the procedure was well tolerated [14]. In 2023, DBS was found to normalise the amygdala response in patients with TRD by monitoring functional magnetic resonance imaging, proving that DBS has great potential for recovery from mental disorders [15].

4. Invasive BCI for motor disabilities

4.1. Amputation

Non-invasive brain-computer interface-controlled prosthesis technology is quite mature and a large number of devices are available for amputees, but there are many problems with the weak EEG signals collected by non-invasive devices, signal noise, and stiffness of movement due to insufficient degrees of freedom. Invasive device-controlled prostheses are still in the development stage and present significant challenges. Further research is underway to overcome the need for invasive experiments on non-human primates.

In 2008, Velliste and colleagues controlled a robotic arm in three dimensions by closely observing activity in a monkey's motor cortex during a self-feeding task. With the assistance of this technology, amputees and paralysed individuals were able to regain use of their arms and hands [16]. A few years later, a 52-year-old tetraplegic was given two 96-channel intracortical MEA implants in his motor cortex by Collinger et al. The individual was able to execute deft and coordinated reaching and gripping motions with the prosthesis after 13 weeks of training [17]. With regard to invasive BCIs, prosthetic control technologies are still struggling on the road to clinical and regulatory validation, from preclinical and pilot studies to multi-centre clinical trials.

4.2. Amyotrophic Lateral Sclerosis(ALS)

The progressive neurodegenerative illness ALS also causes motor difficulties since it separates the brain from the body and impairs the capacity to move on one's own initiative. In 2021, a broadband wireless intracortical BCI was developed. By detecting and analysing the neural activity of the 192 chronically implanted microelectrodes in both participants (Figure 2 shows the human neural signals recorded by the wireless system), it was possible to enable both of them to surf the web and conduct more tablet tasks, even typing on the wireless interface [18]. In 2023, Saal and colleagues looked into the possibility of using hippocampal activity as a source of BCI control in the context of virtual navigation. This research served as a foundation for later studies aimed at improving the usability and efficacy of invasive BCIs for asynchronous real-time control of robotic arms and other assistive devices [19].

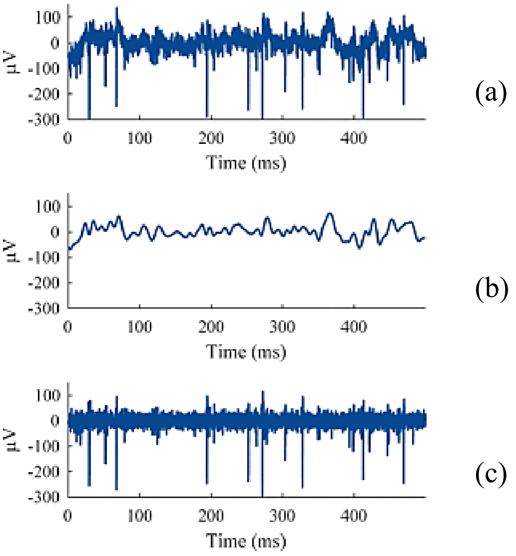

Figure 2. Comparison of neural activity data obtained on a single electrode. (a): the "raw" original neural signal; (b): low-pass filtered (100 Hz cutoff); (c): band pass filtered to extract spikes (250 Hz-7.5 kHz).

4.3. Cerebral Stroke Rehabilitation

Cerebral Strokes, which are typical of acute cerebrovascular disease, are often accompanied by movement disorders such as paralysis. John Donoghue et al. have demonstrated that paralysed people can learn to operate a computer cursor by means of brain signals from the motor cortex. They then went on to clinically realise the ability of paraplegic patients to perform three-dimensional reaching and grasping movements using a robotic arm controller based on a neural interface system by implanting 96-channel MEAs [20].

Additionally, neuroengineering and restorative medicine are working collaboratively towards the development of invasive BCIs for the purpose of motor recovery following a stroke. Brain-controlled functional electrical stimulation (FES) merges BCI technology with FES. This therapy employs BCIs to gather electrical signals from the brain and stimulate the FES, leading to an impairment reduction in chronic moderate-to-severe stroke patients that is statistically significant, clinically relevant, and long-lasting.

5. Conclusion

The network of neurons formed by the central nervous system, spinal cord, and nerves in the peripheral regions that processes and transmits information throughout the body is the primary field of present research. BCI technology, a product of the information age, merges life sciences and information technology, showing great potential in areas such as clinical healthcare, assistive technologies, business, and entertainment. There is already an abundance of research and applications for non-invasive BCIs, therefore, the future emphasis is on the difficulties in converting invasive BCIs from the laboratory to broad clinical application. It is a well-known fact that invasive brain-computer interfaces can collect more precise signals, analyse thoughts, intentions, emotions and cognitive states. And when devices such as electrodes are implanted directly into the brain, they may elicit immune rejection. BCI devices directly stimulate the brain, which poses particular safety concerns. Invasive BCIs imbed electrodes directly into neural tissue, heightening the complication risk during surgery. Electrode problems are also burdensome to resolve or replace post-implantation, necessitating costly post-operative care and maintenance. Furthermore, notable immune responses and ethical concerns are deterrents to large-scale testing of invasive BCIs in clinical human trials. Therefore, the advancement of coding and decoding technology, the investigation of immune response suppression, and the growth of brain science are the prospective research directions for invasive BCIs. Besides, BCIs may also raise privacy issues concerning neurological data, and the ethical ramifications should be anticipated to be addressed in the future with measures like the establishment of protective data regulations.

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