The brain and computer: The neurosurgical interface

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Abstract

Neurosurgery has always had a strong interest in innovating new technologies to improve neurological function and quality of life. Now, novel interventions that modulate central nervous system activity at the nanoparticle, molecular, genetic, cellular, and network level all seem to be on the horizon. Advances in biomedical engineering, including imaging techniques, sensor technologies, bio-signal analyses and classification, and prosthetics, have particularly accelerated the development of brain-computer interfaces (BCI). Clinical translation of BCI technology will require multidisciplinary collaboration and effort to develop all necessary components, including advanced sensor technologies, sophisticated and real-time signal analyses and classifications, and complex effector technologies. Although the field has primarily been driven by basic scientists, neurosurgeons need to play a critical role in the further development of each component of these technologies because of our unique access to the awake and behaving human brain, our perspective with respect to the practicalities of technology implementation in the clinical setting, and because of our historical commitment to improving neurological function and quality-of-life. The current state of BCI research, the challenges, and the critical role that neurosurgeons must play in BCI development are briefly reviewed to advocate for increased neurosurgical involvement and commitment to this emerging translational field.

Key Words: Biomedical engineering, brain-computer interface, brain mapping, electrocorticography, functional neurosurgery, signal processing

INTRODUCTION

Neurosurgery has a long-standing interest and commitment to treating functional disorders and developing technologies and interventions to improve the quality-of-life of patients with neurological impairments. In fact, some of the field’s most important technologies have emerged from this commitment, including the Gamma Knife, which was initially conceived for the treatment of functional disorders, including pain, psychiatric disease, and movement disorders, and deep brain stimulation (DBS). Now, advances in the field of biomedical engineering, including imaging techniques, sensor technologies, bio-signal analyses and classification, and prosthetics, have created yet another opportunity for neurosurgery to help innovate technologies to restore function to patients with neurological impairments – the brain-computer interface (BCI). While the prospect of controlling a computer or any other interactive device with the brain was once only a topic of science-fiction books and movies, technological advances now allow real-time assessment of human brain function...
and connectivity that were previously unappreciable.\textsuperscript{5,16} It is critical that neurosurgeons remain aware of the basic scientific developments in this field and lead the translational effort to bring these technologies to reality because of the unparalleled access that neurosurgeons have to the awake and behaving human brain, the unique perspective of neurosurgeons with respect to the practicalities of BCI development, and neurosurgeons’ genuine commitment to improving patients’ quality-of-life and function.

Despite a demonstrated commitment to functional disorders, most of contemporary neurosurgery focuses on structural pathology, such as the extirpation of tumors and vascular malformations, the treatment of degenerative spine disease, and the securing of intracranial aneurysms. While these are major sources of morbidity and mortality, there are numerous patients with impaired quality-of-life for whom neurosurgery has not been able to offer significant life-changing interventions, including those with stroke, spinal cord injury, and neurodegenerative processes that at least initially spare the cortex, such as amyotrophic lateral sclerosis. The potential impact on patients and healthcare costs is tremendous. On average, someone in the United States has a stroke every 40 seconds.\textsuperscript{15} As such, it is one of the leading causes of disability both in the United States and the developing world.\textsuperscript{7,9} In the United States alone in 2001, disability due to stroke accounted for 9.35 million disability adjusted life years (years of life lived in less than full health).\textsuperscript{14} Stroke and its consequences account for at least 3% of total healthcare expenditure and are projected to cost the US economy $2.2 trillion dollars between 2005 and 2050.\textsuperscript{7} Because of its significant cost and impact, there is a call for increased research funding to prevent stroke and its consequences.\textsuperscript{10,20} Although not as prevalent, spinal cord injury (SCI) and disease (e.g., amyotrophic lateral sclerosis) are also significant sources of functional disability because they are physically incapacitating but rarely fatal: despite only 12,000 new cases of spinal cord injury per year, there are approximately 250,000 people living with spinal cord injury in the United States.\textsuperscript{19} Only 35% of SCI patients are employed 20 years after injury. The estimated lifetime healthcare costs and living expenses of SCI patients can be over $3,000,000 plus $65,000 per year in lost wages, benefits, and productivity.\textsuperscript{19} Advances that restore even a modest level of independence to these severely disabled patients can potentially significantly improve their quality-of-life and reduce societal costs. While these diseases do not have gross structural lesions that can be treated surgically, advances in nanotechnology, molecular and cellular biology, and electrophysiology in the near future will likely provide insights and neurosurgical targets for therapeutic intervention using novel technologies. Modulation at the nanoparticle, molecular, genetic, cellular, and network level all seem to be on the horizon.

The fields of neurology and neurosurgery have long incorporated various brain interfaces into clinical practice, particularly in the domain of epilepsy. Electroencephalography (EEG) is in fact one of the earliest such interfaces used to assess normal and pathological brain activity. Direct electrical stimulation of the brain represents another unparalleled and powerful interface that neurosurgeons have taken advantage of for decades to gain insight into the functional neuroanatomy of the human brain, best demonstrated by the works of Penfield and Jasper.\textsuperscript{21} Contemporary deep brain stimulation (DBS) for the treatment of movement disorders is the closest neurosurgery has come to providing a chronically implanted “brain--computer interface” for therapeutic and functional purposes.\textsuperscript{2} Although an important and critical step toward the development and implementation of advanced BCI, current DBS technology lacks a computational component. It does not sense brain activity (or any other type of feedback), does not perform “computations,” and therefore does not alter therapy or improve function or quality-of-life in a closed-loop or automated manner. Instead, a practitioner must “close the loop,” assessing the patient’s clinical exam, “compute” the importance of these findings, and make alterations to the prescribed therapy.

Closed-loop BCI, for which the technology and expertise is rapidly emerging, will ideally incorporate (1) advanced sensor technologies (e.g., chronic recordings of neuronal unit or field potential activity), (2) sophisticated and real-time computational components for signal analyses and classification, and (3) complex effector technologies to provide therapeutic benefit based on the recorded and processes signals. Effectors may include, for example, prosthetic limbs to “act out” detected motor signals, displays to convey language, thought, or emotion, or even closed-loop brain stimulation. Each component of a BCI requires critical input and collaboration from multiple fields including neuroscience, physiology, biomedical engineering, computer sciences, statistics, and clinicians. Given that many proposed BCI rely on invasive recordings of human neurophysiological signals, neurosurgeons must play a central, collaborative, and contributing role in the development and validation process. Given the potential impact on patients’ quality-of-life, neurosurgeons must use their unique position to accelerate progress in the field.

The optimal brain mapping signal for controlling BCI remains unclear. Ideally, the brain signal used should provide the best combination of information (i.e., sensitivity and specificity), resolution (both spatial and temporal), spatial sampling, fidelity, signal-to-noise, and practicality. Some noninvasive brain mapping modalities, such as functional magnetic resonance
Imaging (fMRI) and magnetoencephalography (MEG), are likely impractical for clinical application due to insufficient temporal resolution (e.g., fMRI) and size of the imaging apparatus (e.g., fMRI and MEG). On the other hand, there is considerable debate about the appropriateness of other mapping techniques, including EEG, electrocorticography (ECoG), and unit recordings. Unit recordings provide the highest spatial and temporal resolution, representative of the most basic unit of electrophysiological communication (i.e., the action potential), and have been used extensively in animal and human studies to gain insight into neural representations of motor behavior and cognition.\cite{5,18,24} Schwartz and colleagues reported that unit activity could in fact be used by primates to control and prosthetic limb and self-feed\cite{21} and Donoghue and colleagues have provided several reports of using unit-activity to control a computer cursor and a prosthetic hand in real time.\cite{10,22} In contrast to unit recordings, EEG and ECoG provide poorer spatial and temporal resolution but much greater spatial sampling and a measure of population level activity. While it has long been assumed that these signals would not contain sufficient detail and specificity for BCI applications, several reports have confirmed the specificity and utility of both motor and language-related signals for real-time BCI-based control.\cite{12,16,17} Besides signal content, there are outstanding issues with respect to practicality of implementation – whereas it can be difficult to maintain unit recordings for hours, days, or weeks. Clinical experience has already established that EEG and ECoG signals can be reliably measured for several weeks (if not longer) continuously. Since it is highly likely that future real-time multidimensional BCI will be implanted using techniques similar to those used for contemporary DBS, neurosurgeons must play a critical role in the design and implementation of sensor development, providing a valuable input with respect to practicality, durability, and potential roadblocks in implementation. Clinical neurosurgeons and neurologists have in fact been critical in the significantly increased interest and study of field potential signals recorded using ECoG because of the extensive established experience using this brain mapping modality for epilepsy.\cite{8} Ultimately the optimal signal source for various BCI applications will likely depend on the intended purpose of the device.

Development of applicable and relevant signal analysis algorithms for BCI requires, at a minimum, simultaneously recorded human brain signals and behaviors upon which to work. Neurosurgery is the ultimate gatekeeper to such data because of clear ethical constraints which limit access to invasive recording of human brain signals without clinical indications. Neurosurgery has a long history of exploiting awake brain surgery to gain insight into brain function and organization, including perhaps most significantly the characterization of the somatosensory homunculus.\cite{21} Collaboration and leadership of neurosurgeons to acquire the necessary dataset to study human electrophysiology and to develop sophisticated and, ideally, real-time analysis algorithms to derive BCI command signals. This need is increasingly recognized and the field only stands to benefit from continued interest and collaboration. In some cases, neurosurgeons have even taken the lead in developing the signal analysis algorithms identifying methods to differentiate, for example, individual finger movements.\cite{11}

The output arm of a brain-computer interface, or effector, can manifest, among other possibilities, as a prosthetic limb, computer software, or physiologic stimulation for neuromodulation. The latter is likely the most intriguing to neurosurgeons, given the recent reports of progressive neuromodulation and clinical improvement over months with brain stimulation in trials for both epilepsy and obsessive-compulsive disorder.\cite{6,9} The recent NeuroPace clinical trial likely represents the first clinical implementation of a closed-loop BCI that measures electrophysiological activity, detects pathological activity, and delivers brain stimulation to improve the quality-of-life of patients with medically refractory epilepsy (by reducing seizure frequencies).\cite{1} Technological advances in neuroimaging and noninvasive brain mapping, including functional magnetic resonance imaging (fMRI), positron emission tomography (PET), diffusion tensor imaging and tractography, and studies of resting state functional connectivity using MRI (rsfMRI), provide insights into physiological and pathological circuits mediating health and disease. These noninvasive mapping techniques will likely play a critical role in identifying additional targets of pathology and therapeutic efficacy for a spectrum of neurologic and psychiatric disease, like they did in identifying the subgenual cingulate DBS target for the treatment of depression.\cite{13} Development of further technologies along similar lines will require and significantly benefit from continued input of neurosurgeons who aim to treat medically refractory illnesses.

The potential growth in the field of BCI positions functional and restorative neurosurgery to be one of the areas in neurosurgery with the most significant growth in the near future. The advances in biomedical engineering, neuroimaging, computer science, and statistics have made it increasingly possible to both detect and intervene in disease processes that were previously believed to not be amenable to surgical intervention. BCI holds the promise of restoring function and quality of life to patients with strokes, spinal cord injury, amyotrophic lateral sclerosis, amputations, and other neurodegenerative disease. The prospect of BCI reinforces the notion that neurosurgeons can not only help patients by removing pathology from the brain but in fact by intervening in the complex
physiology and networks within this organ to help improve the patient’s quality of life.

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