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BCI Meeting 2005—Workshop on Signals and Recording Methods

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***Abstract*—This paper describes the highlights of presentations and discussions during the Third International BCI Meeting in a workshop that evaluated potential brain–computer interface (BCI) signals and currently available recording methods. It defined the main potential user populations and their needs, addressed the relative advantages and disadvantages of noninvasive and implanted (i.e., invasive) methodologies, considered ethical issues, and focused on the challenges involved in translating BCI systems from the laboratory to widespread clinical use. The workshop stressed the critical importance of developing useful applications that establish the practical value of BCI technology.**

***Index Terms*—Brain–computer interface (BCI), electrophysiological signals, rehabilitation.**

I. Introduction

This workshop, which was part of the 2005 BCI meeting, addressed the characteristics, advantages, and disadvantages for brain–computer interface (BCI) use of different brain signals and recording methods with particular reference to development of clinical applications. The major issues considered included the characteristics, capacities, and needs of people likely to benefit from a BCI; the advantages and disadvantages of electroencephalographic (EEG), electrocorticographic (ECoG), and intracortical signals; other possible signal modalities; the ethical issues associated with BCI research and use; and the transition from the laboratory to widespread clinical use. The participants included clinical and basic neuroscientists, cell biologists, engineers, biophysicists, psychologists, and clinicians. The format included individual presentations and panel-led discussions.

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II. User Populations

BCI users are often categorized according to the disorders responsible for their disabilities, such as amyotrophic lateral sclerosis (ALS), brainstem stroke, spinal cord injury, or cerebral palsy. However, decisions regarding whether or how BCI technology might be useful to these users usually depend more on the extent of their disability than on its origin. In this regard, potential users fall into three relatively distinct classes.

The first class consists of people who are truly totally locked-in (e.g., due to end-stage ALS or severe cerebral palsy), who have no remaining useful neuromuscular control of any sort, including no eye movement. Although this class is very small, it is often considered to be the first target group for BCI applications. However, in reality, efforts to demonstrate effective BCI operation by these individuals encounter a number of difficult challenges. It is often unclear, for example, whether cognitive functions remain intact, whether vision is adequate to support BCI operation, and if not, whether an auditory or other alternative will suffice, and whether the user can or will maintain a state of alertness adequate for reliable BCI operation. In practice to date, these or related issues have been major impediments to BCI usage by these users. Each person requires a comprehensive and individualized approach that goes far beyond the much simpler procedures effective in those who are not totally locked-in. On the other hand, if people progressing toward this level of disability (e.g., those in the early or middle stages of ALS) begin to use BCI technology before they become totally locked-in, they may be able to continue to use it effectively after they lose all motor function.

The second class of potential BCI users comprises those who retain a very limited capacity for neuromuscular control. This group includes people who retain some useful eye movement or enough limb muscle function to operate a single-switch system. Such control is often slow, unreliable, or easily fatigued [5]. This group is much larger than the first, and includes many people with late-stage ALS, brainstem stroke, and severe cerebral palsy. The advent of widely available life-support technology, particularly ventilators, enables these individuals to survive indefinitely, and numerous studies now show that with adequate physical and social support they can lead lives that they and their families and friends consider worthwhile and enjoyable [12], [20], [23], [27], [32], [45]. Thus, there is substantial impetus for developing BCI communication and control technology for this group. Furthermore, current or readily achievable BCI systems may provide communication and control capacities (e.g., for simple word processing, environmental control, entertainment access) comparable to, or even better than, that achievable with their residual neuromuscular control.

The third class of potential BCI users, which is the largest of all, includes those who still retain (and can be expected to continue to retain) substantial neuromuscular control, particularly speech and/or hand control, and can, therefore, operate a wide range of assistive communication and control devices. For this group, as well as for users without disabilities, BCI technology, whether currently available or likely to be available in the near future, has little to offer (though it might be useful in very specific situations, such as when hands-free control is required). It will only be if and when BCI speed, accuracy, and precision of control substantially exceed current levels that this technology will become a significant option for this class of potential users.

Thus, at present, users of the second class (including those progressing toward the first class) constitute the principal candidates for BCI communication and control applications. Substantial anecdotal experience indicates that there are many such individuals with minimal remaining useful motor function. People with late-stage ALS constitute the largest number. People with severe cerebral palsy, brainstem stroke, and a variety of other neuromuscular disorders comprise the rest of this group.

III. Available Control Signals

While most BCI systems use electrical signals produced by brain activity to derive user intent, a variety of other signals could conceivably be used (for review [1], [19], [42]). These include signals obtained by functional magnetic resonance imaging (fMRI); near-infrared spectroscopy (NIRS); magnetoencephalography (MEG); and positron emission tomography (PET) (e.g., [3], [6], [7], [10], [13], [41], [44]). BCIs using fMRI or NIRS measure changes in the brain's hemodynamic response. Although they may provide good spatial resolution, they have poor temporal resolution. In addition, fMRI and PET require bulky expensive equipment and are technically demanding. MEGs measure the brain's magnetic activity, and hence MEG BCIs might provide real-time control with excellent spatial and temporal resolution. However, this option, like fMRI, requires a superconductor and is, therefore, bulky, expensive, and impractical for widespread clinical use. As a result, while other signal types merit further research (particularly NIRS), only electrical signals are likely to be of significant practical value for clinical use in the near future.

As Fig. 1 illustrates, the electrical fields produced by the brain can be detected at the scalp (EEG), at the cortical surface (ECoG activity), or within the cortex [local field potentials (LFPs) or neuronal action potentials (spikes)]. Each alternative has advantages and disadvantages. EEG recording is easy and noninvasive. At the same time, however, it has relatively limited topographical resolution and frequency range. It may also be contaminated by artifacts such as electromyographic (EMG) activity from cranial muscles or electrooculographic (EOG) activity. While the potential speed and accuracy of EEG-based BCI operation has often been assumed to be modest, recent studies (e.g., [43]) indicate that it can provide multichannel function previously thought to require implanted recording electrodes. At the same time, EEG requires continued maintenance (presumably by caregivers) of stable relatively low-impedance electrode contacts at specific locations on the scalp. In addition, users may object to the cap or other device needed to maintain the electrodes in place. Thus, more convenient and less conspicuous EEG electrode methods are highly desirable (e.g., [36]).

Up to the present, surface cortical recording has been possible almost exclusively from patients implanted with ECoG electrode arrays for a few days prior to epilepsy surgery. Thus, while results are promising (e.g., [22]), BCI ECoG studies have been very limited. ECoG has much better topographical resolution and frequency range than EEG and is essentially free from artifacts like EMG and EOG. Thus, ECoG has substantial promise for BCI applications. At the same time, ECoG requires implantation of electrode arrays that have long-term stability and give consistent performance. While the technology for permanent implants exists, it has yet to be rigorously tested and configured for clinical use. Furthermore, the nature and significance of the long-term effects of such implants remain unknown and will require preclinical studies in animals.

Intracortical recording, or recording in other brain structures, can provide the highest resolution signals. These signals are individual neuronal action potentials (spikes) or LFPs that reflect the combined activity of nearby neurons and synapses. Most BCI-related work up to the present has been in animals and has focused on spike activity (e.g., [2], [30], [37], [38]). The few studies assessing LFPs suggest that they may be as useful or more useful than spikes (e.g., [24]). Limited human studies are underway (e.g., [14]). While the control achieved has been reasonably impressive, long-term stability and transferability from highly constrained laboratory situations to more complex clinical environments remains uncertain. Most important, this approach entails insertion of multiple electrode arrays within brain tissue. Thus, it faces major as yet unresolved issues related to acute and chronic tissue damage and long-term recording stability [11], [25], [35], [39], [40]. Present-day arrays clearly evoke a complex continuing process of tissue reaction [11], [18], [35], [39]. While some electrodes may continue to function for long periods, many lose the ability to record spike activity quite early [11], [40]. At the same time, recent results are more encouraging [34], and efforts to reduce or control the reaction to implanted arrays and thereby promote long-term functional stability are just beginning [21], [26], [31], [33]. For intracortical electrodes as for ECoG electrodes, long-term clinical use will require wholly implanted technology that incorporates telemetry, because it is essential to avoid the percutaneous connections that are used in acute studies but provide routes for infection in long-term applications.

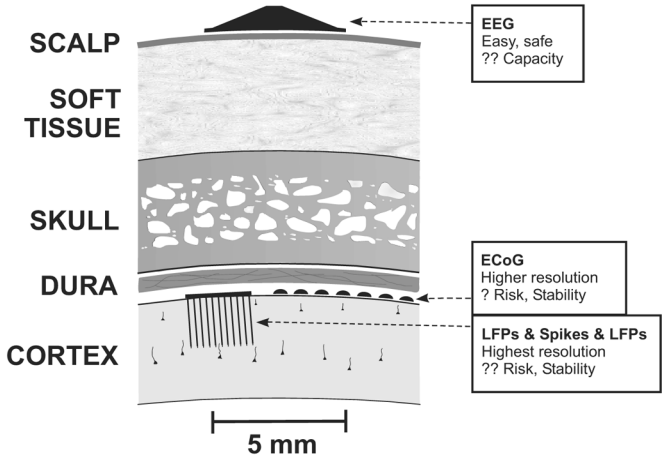

Fig. 1. Brain's electrical fields can be detected by electrodes (black) on the scalp (EEG), on the cortical surface (ECoG activity), or within the brain [LFPs and neuronal action potentials (spikes)]. See text for discussion.

The eventual clinical value of each of these recording options will reflect the capabilities of the communication and control applications it can support and the degree to which its medical risks and technical limitations can be overcome. The relative practical usefulness of EEG, ECoG, and intracortical methods remains to be determined. Comprehensive evaluation of the characteristics, capacities, and safety of each recording method is essential, and will be facilitated by software that can be readily adapted to different signals and operating protocols (e.g., [29]).

IV. Ethical Issues

BCI research and development raises three sets of ethical issues. The first set includes issues that confront any medical research effort that involves any level of risk. In the case of BCI technology, it applies primarily to invasive methods, such as ECoG or intracortical recording. Implantation of electrode arrays within brain or even just on the cortical surface entails some measure of acute trauma. It may initiate prolonged reactive processes leading to scarring and possibly significant neuronal loss and risk of infection, particularly if long-term percutaneous connections are necessary. In addition, there is risk of functional failure over time, leading to additional surgery for removal or replacement.

Human research investigations of implanted devices will require preclinical studies that address these risks and establish the usefulness of

the technology. Risk–benefit considerations will ultimately determine whether implanted devices (whether in or on the cortex) or noninvasive methods will best provide BCI function for a given patient. Animal research to establish methods to ensure long-term performance of implanted devices and technology development to provide wireless systems for data and information transfer from and to these devices must be completed before they will be suitable for widespread clinical application.

Beyond these standard questions of risks and benefits, all BCI research and development, whether it involves noninvasive or implanted methods, raises two additional and unique sets of ethical issues. One is the potential invasion of privacy inherent in the possibility that a BCI might be used to obtain information (e.g., answers to specified questions) from a person without consent. However, most, and possibly all, BCI-based communication requires active interaction between the user and the BCI system. BCI usage is a voluntary and often effortful activity, similar to conventional voluntary motor acts, except that it does not involve peripheral nerves and muscles. While P300-based methodology has been proposed as a promising new lie-detection method [8], [9], [16], more recent work indicates that this technique does in fact require the active participation of the individual [15], [28].

The other set of unique BCI-related ethical issues are those related to the creation of cyborgs. A "cyborg," as defined in the Oxford English Dictionary [4] is "a person whose. . . capabilities are extended beyond normal human limitations by a machine; an integrated man–machine system." All BCIs, whether they use noninvasive or implanted methods, take brain signals associated with normal brain activity and convert them into a wholly new output channel. The brain's normal outputs are the result of complex interactions of cortical, subcortical, and spinal cord neuronal populations, and are all expressed through the spinal motoneurons that control muscles. Thus, the final outputs undergo multilevel preprocessing. In contrast, BCIs take signals from one or several brain areas and use them directly as control signals for devices such as cursors or prostheses. Thus, BCIs essentially reformat CNS operation, and create a cyborglike combination of brain and machine.

This CNS/BCI cyborg may have new capacities beyond those of the normal CNS. It might, for example, be able to act more rapidly or to control more outputs simultaneously. Of more potential concern is the possibility that BCI usage could induce widespread changes in brain functions that go well beyond changes in the brain area directly responsible for the BCI signals (e.g., [17]). Because activity-dependent plasticity is ubiquitous throughout the CNS, continued BCI usage could have complex long-term impact on other brain areas and on many aspects of CNS operation. Furthermore, a CNS/BCI cyborg might not possess the same censoring capacities that oversee conventional neuromuscular output channels. Thus, inappropriate actions that would normally be considered and not executed might conceivably go forward because they originated from the signals emanating from a particular cortical area rather than from normal spinal motoneuron activation. The present primitive state of BCI development means that such concerns will remain only theoretical for the near future. Nevertheless, these issues are certainly interesting and potentially important and may require substantial attention in the future.

V. Moving From the Laboratory to the Home

The purpose of BCI research and development is to restore communication and control capacities to people with severe motor disabilities. Thus, this work must solve the problems attendant on transferring technology from the laboratory to widespread clinical use. There are at least five critical issues.

First, the BCI must be easy to use. BCI operation must be simple and straightforward so that it can be handled by the user and caregivers on their own, with minimal continued technical support. Reliable electrodes and user-friendly software are necessary.

Second, the BCI must operate consistently in the user's home without significant disruption by electrical noise generated by ventilators, wheelchairs, household appliances, or other devices. Most people with severe disabilities live surrounded by an extensive array of electronic equipment.

Third, unlike most laboratory BCI systems, which tend to be physically large and complex, home BCI systems need to be compact so that they occupy little space and have minimal impact on the user's immediate environment.

Fourth, BCI use should not interfere with normal daily activities. Users with severe disabilities have demanding schedules involving many often prolonged interactions with caregivers, physiotherapists, and other support personnel. BCI usage should improve these interactions, not impede them.

Fifth, and perhaps most important, the BCI must provide capacities that the user actually wants. This is not a trivial requirement. Users of assistive technology frequently want capacities different from those that researchers or therapists may assume to be most desired. As a result, each home BCI installation will require careful preliminary discussions with user and caregiver and will almost certainly entail adjustments or specialized application implementations that are, to some degree, unique to each user.

VI. Conclusion

At present and for the immediate future, BCI-based communication and control will be most useful to people who retain only minimal and unreliable voluntary muscle control; and clinically useful BCIs are likely to be those that use electrophysiological signals, whether obtained noninvasively from scalp electrodes or invasively from implanted devices. The relative advantages and disadvantages of the different electrophysiological BCI methods remain uncertain, and their clarification will require careful human and animal studies. BCI research and development raises standard ethical issues and unique ethical issues related to their possible abuse and to their probable complex effects on CNS function. Achievement of the central goal of BCI research—communication and control for those for whom conventional assistive technology is inadequate—will require home BCI systems that are effective, easy to use, reliable, and inobtrusive.

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