33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

An Optical Brain Computer Interface for Environmental Control

Hasan Ayaz, Patricia A. Shewokis, Scott Bunce, and Banu Onaral, *Fellow, IEEE*

Abstract— **A brain computer interface (BCI) is a system that translates neurophysiological signals detected from the brain to supply input to a computer or to control a device. Volitional control of neural activity and its real-time detection through neuroimaging modalities are key constituents of BCI systems. The purpose of this study was to develop and test a new BCI design that utilizes intention-related cognitive activity within the dorsolateral prefrontal cortex using functional near infrared (fNIR) spectroscopy. fNIR is a noninvasive, safe, portable and affordable optical technique with which to monitor hemodynamic changes, in the brain's cerebral cortex. Because of its portability and ease of use, fNIR is amenable to deployment in ecologically valid natural working environments. We integrated a control paradigm in a computerized 3D virtual environment to augment interactivity. Ten healthy participants volunteered for a two day study in which they navigated a virtual environment with keyboard inputs, but were required to use the fNIR-BCI for interaction with virtual objects. Results showed that participants consistently utilized the fNIR-BCI with an overall success rate of 84% and volitionally increased their cerebral oxygenation level to trigger actions within the virtual environment.**

I. Introduction

A Brain Computer Interface (BCI) is defined as a system that captures and transforms signals originating from the human brain into commands that can control external applications or instruments. BCI provides a route for neural output that does not involve the neuromuscular system [1]. BCI systems have a wide range of potential applications, including rehabilitation and assistive use for severely paralyzed patients to help them communicate and interact with their environments, as well as neural biofeedback to self-regulate brain activity for treating various psychiatric conditions and/or to augment the interactivity of healthy individuals. The majority of BCIs developed to date have employed operant training of direct neurophysiological responses, including the electroencephalogram (EEG), event-related potentials and event-related synchronization/desynchronization [1, 2]. Compared to neuroelectric studies, there have been a few studies involving BCIs that utilized hemodynamic signals from the brain [3, 4].

A popular form of functional magnetic resonance imaging (fMRI), the blood oxygen level dependent, or BOLD response, relies on the measurement of evoked hemodynamic response based on the oxygen metabolism during neural activity. With the advent of real-time processing capabilities, fMRI has begun to be utilized for BCI research. Initial studies used the supplementary motor area (SMA) for monitoring activation changes while participants perform motor control or motor imagery [5-7]. Since fMRI can measure activation from all parts of the brain, experimenters also used fMRI neurofeedback to train human participants in the self-regulation of localized brain regions. Specific cortical and subcortical areas, such as the supplementary motor area, the posterior part of the superior temporal gyrus, parahippocampal place area (PPA), the anterior cingulate cortex (ACC), insula, Broca's area, and amygdala have been studied in fMRI-BCI paradigms [5-17]. Results from these studies demonstrate that fMRI-BCI provides a novel approach in neuroscience for studying brain plasticity and functional reorganization following sustained training of volitional control of localized brain regions. However, several constraints of current fMRI instrumentation limit the practical application of fMRI-BCI systems, i.e. the systems confine participants to restricted positions, may expose individuals to potentially loud noises if not mitigated, and the signals are highly sensitive to motion artifact. Functional near-infrared (fNIR) spectroscopy is a relatively new noninvasive technology that can be used to monitor concentration changes of both oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) at the cortex [18, 19]. It measures hemodynamic changes in the brain similar to fMRI, but unlike fMRI, fNIR is quiet (no operating sound), provides higher temporal resolution and participants can be monitored in ecologically valid positions (e.g., sitting at a computer, even walking on a treadmill). Moreover, processing of fNIR signals is computationally less intensive and can provide real-time feedback without delay and new motion rejection algorithms can applied without time shift [20]. These qualities pose fNIR as an ideal candidate for monitoring brain activity related hemodynamic changes not only in laboratory settings but also under working conditions and for deployment in BCI applications.

To date, applications of optical brain activity monitoring in BCI research is limited. It is known that motor control tasks such as finger tapping generates a well understood spatiotemporal pattern that can be detected by optical brain imaging methods [21]. Building on these findings, motor control and motor imagery have been utilized as control paradigms for BCI by monitoring motor cortex activity with fNIR [3, 4, 21, 22]. Evidence indicating that fNIR is

Manuscript received March 25, 2011. B. Onaral, and H. Ayaz are with the School of Biomedical Engineering Science & Health Systems, Drexel University, Philadelphia, PA 19104 USA (Direct correspondence to phone: 215-571-3709; fax: 215- 571-3718; e-mail: ayaz@drexel.edu).

P. A. Shewokis is with the College of Nursing and Health Professions, Drexel University, Philadelphia, PA 19104 USA.

S. Bunce is with the Penn State Hershey Neuroscience Institute, Penn State University, Hershey, PA 17033 USA.

sensitive to attention and cognitive load tasks [23, 24] led some investigators to monitor prefrontal cortex while participants performed such volitional mental tasks as mental arithmetic as BCI control paradigms [25-28].

In an effort to develop a more natural control mechanism, (that does not require a secondary mental task) other investigators reported using an *intention*, a subjective preference for a beverage [29] to select a drink on a computer screen. In an effort to develop a more naturalistic input interface for a BCI system we have recently demonstrated that participants can learn to utilize a select cortical region within dorsolateral prefrontal cortex as an input mechanism for a BCI through fNIR-based neurofeedback [30].

In this study, our aim was to deploy the fNIR-neurofeedback that we have reported in [30, 31] in a BCI setting for environmental control. We incorporated the control paradigm within 3D virtual environments that were created and edited by the MazeSuite (www.mazesuite.com) software package [32, 33]. Users navigated within the virtual environment using standard keyboard inputs. However, to complete the mazes, they were required to trigger responses from interactive objects by first approaching them (proximity based activation) and then engaging with the fNIR-BCI that they were trained by operant conditioning.

II. Method

A. Functional Near Infrared Spectroscopy

The continuous wave fNIR system (fNIR Devices LLC; www.fnirdevices.com) used in this study was connected to a flexible sensor pad (Figure 1) that contained 4 light sources with built in peak wavelengths at 730 nm and 850 nm and 10 detectors designed to sample cortical areas underlying the forehead. With a fixed source-detector separation of 2.5 cm, this configuration generates a total of 16 measurement locations (voxels) per wavelength [34]. Data acquisition and visualization were conducted using COBI Studio software (Drexel University). This system records two wavelengths and dark current for each of the 16 voxels, totaling 48 measurements for each sampling period. Details of the fNIR technology can be found in [24, 31, 33].

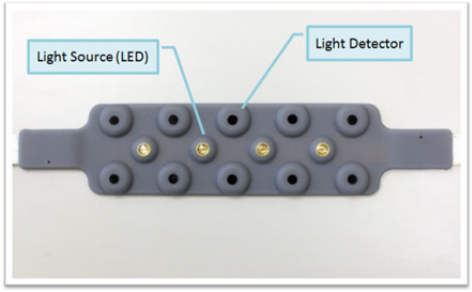

Fig. 1. Flexible fNIR head sensor with 4 LEDs and 10 detectors collect data from 16 measurement locations over forehead.

B. Experiment Setup

Ten healthy (five males) right-handed participants (laterality quotient scores 71.6 ± 24.7 on Edinburgh Handedness Inventory) volunteered for this two day study. During the experiment, fNIR sensor pad was positioned over the forehead of the participants while they were sitting in front of a computer screen and keyboard. Every 500ms, raw fNIR signals from 16 voxels (2 wavelengths and 1 dark current=48 channels) were sampled by COBI Studio software operating on a data acquisition computer and streamed through a wired network to the Protocol Computer.

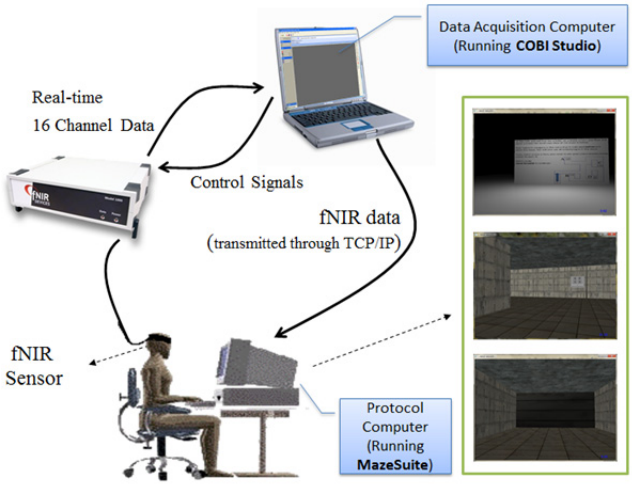

Fig. 2. Experiment Setup for fNIR-BCI that includes data acquisition, processing and rendering interactive 3d environment based on user input.

C. Experiment Protocol

Prior to the experiment, all participants had been trained to control the size of a bar graph using fNIR neurofeedback calculated from signals generated from prefrontal cortex (BA10) approximately underlying International 10-20 site Fp1 [30, 31, 34]. Participants were presented with a vertical or horizontal full screen progress bar. Changes in the height or length of the bar was calculated from changes of oxygenation level compared to baseline within left dorsolateral prefrontal cortex close to Fp1. Participants were instructed to simply use their mind to change the size of the bar. Participants used a trial and error method to increase bar length using feedback from the bar on the computer screen. For each trial, participants first relaxed and then engaged in an attempt to increase the bar length. Participant responses were shaped through operant conditioning via direct neurofeedback on the screen; increased or decreased oxygenation at Voxel 6 (Fp1) resulted in concomitant increases or decreases in the onscreen bar length. Using this method, participants were able to learn to control the bar length through mental focus.

In the current study, the bar graph was integrated with interactive game objects (doors); participants were asked to open these doors using the same mental task they had learned to increase the bar lengths. A virtual maze environment, Arena, was designed to have 5 doors. The first door was the entrance door; the others were labeled A through D. The start position was just in front of the entrance door and the exit (end regions) was behind doors A, B, C and D. To navigate the 3D environment from beginning to end, users needed to open two doors. A single *session* required navigating the Arena from beginning to the end

using both keyboard button controls (for navigation) and also by opening two doors (only through interaction with the fNIR BCI protocol). Just before users entered the Arena, they saw the target door name for that session displayed on a blank screen; either A, B, C or D. Their objective was to exit the maze by entering the door indicated at the beginning of the session. This was intended to provide an overall goal for accomplishing the fNIR-BCI task.

A single *trial* involved approaching a door (timed by the participant). When the participant's distance to the door reached a pre-selected threshold value, the door activated i.e. started shaking, indicating that it was activated (proximity based). The rest period was selected as the data segment that started 5 seconds before the proximity based activation and continued until the activation time. If participants could increase the bar size over 85% the door opened. For each trial, if unsuccessful, participant could retry and attempt again. The experiment required two days of participation; on each day participants completed 10 sessions of the Arena totaling 40 trials per subject and 400 trials total.

D. Online Processing

Online processing was performed in real-time to calculate oxygenation changes. Raw optical intensity values in two wavelengths (730nm and 850nm) at each sampling instance were received through TCP/IP protocol at a frequency of 2Hz. Oxy-Hb and dexoy-Hb concentration changes were calculated by modified beer lambert law [31]. Timing information markers for onset and offset of rest and task periods were used to identify optical data source. The size of the visual feedback bar was modeled as a linear transformation of the oxygenation changes of Voxel 6, corresponding to the voxel location at Fp1.

E. Statistical Analysis

A 2 x 2 (Condition X Day) repeated measures ANOVA was calculated for oxy-Hb and deoxy-Hb. The within-subjects factor was condition with two levels rest and task, and the last factor was day with two levels: day 1 and day 2. Post-hoc analyses consisted of Tukey multiple comparison tests were used. The significance criterion for the tests was $\alpha = 0.05$.

III. Results

Comparison of mean deoxy-Hb and oxy-Hb concentration changes for rest and task periods are presented in Figures 3 and 4, respectively. Repeated measures ANOVA indicated that there was a main effect for condition (rest vs. task) for voxel 6 (that was the source of neurofeedback) on both oxy-Hb ($F(1,719) = 61.10$, $p<0.0001$) and dexoy-Hb ($F(1,719) = 41.85$, $p<0.0001$).

The performance of the overall fNIR-BCI was measured by comparing the successful to the total number of trials within all sessions. Each participant's performance was calculated by dividing successful trials by the number of attempts for both days as listed in Table II below.

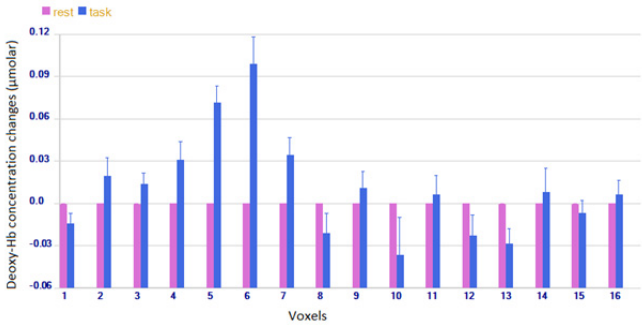

Fig .3. Spatial comparison of average deoxy-Hb concentration changes during rest and task periods with peak activation at voxel 6. Error bars are standard error of the mean (SEM).

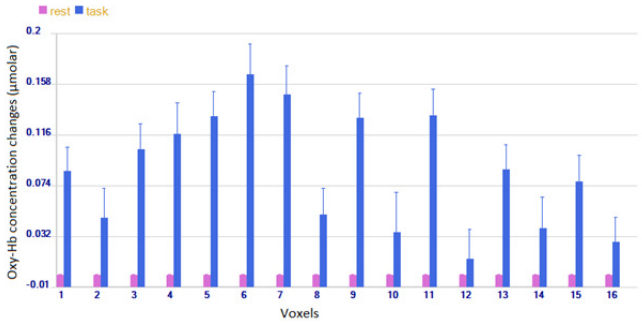

Fig .4. Spatial comparison of average oxy-Hb concentration changes during rest and task periods with peak at voxel 6. Error bars are SEM.

TABLE I
Statistical comparison of rest vs. task periods for voxel 6 (Two-tailed paired T-tests; N=400; 10 participants x 40 trials; df=399)

	t	p	Mean Diff	Lower Limit %95 CI	Higher Limit %95 CI
Oxy-Hb	6.62	<0.001	0.166	0.116	0.215
Deoxy-Hb	5.11	<0.001	0.099	0.061	0.137

TABLE II
fNIR-BCI performance as measured by successful trial percentage

Participant	Day1	Day2	Averages
1	76.9	100.0	88.5
2	87.0	90.9	88.9
3	71.4	90.9	81.2
4	71.4	90.9	81.2
5	80.0	100.0	90.0
6	100.0	100.0	100.0
7	100.0	90.9	95.5
8	64.5	58.8	61.7
9	71.4	62.5	67.0
10	83.3	100.0	91.7
Averages	80.6	88.5	**84.6**

IV. Discussion

Results indicate that after training, participants can engage with our fNIR-BCI paradigm and volitionally up-regulate their localized brain activity to interact with their environment and trigger events in a virtual environment. Participants were able to volitionally increase both oxy-Hb and deoxy-Hb concentrations, comparable to previous studies [30, 31].

This fNIR-BCI has a binary selection protocol, but it could be extended to trigger other actions to allow the continuous control of properties of objects such as location

and size. This study represents the first report of an fNIR-based BCI that utilizes neurofeedback in the direct operant conditioning of neural response. Unlike previous studies that monitored activation in the prefrontal cortex, this method does not require the operator to perform an unrelated cognitive task such as mental arithmetic or verbal fluency to engage the BCI. These results suggest that using the spatial localization of fNIR, a BCI can be developed around a system that uses direct operant conditioning of cortical activity as a more ecologically valid form of operator input to the BCI system.

ACKNOWLEDGMENT

Authors would like to thank Adrian Curtin for his help with MazeSuite integration.

REFERENCES

[1] J. R. Wolpaw, N. Birbaumer, D. J. McFarland, G. Pfurtscheller, and T. M. Vaughan, "Brain-computer interfaces for communication and control," *Clin Neurophysiol,* vol. 113, pp. 767-91, Jun 2002.

[2] N. Birbaumer, "Brain-computer-interface research: Coming of age," *Clinical Neurophysiology,* vol. 117, pp. 479-483, 2006.

[3] R. Sitaram, A. Caria, and N. Birbaumer, "Hemodynamic brain-computer interfaces for communication and rehabilitation," *Neural Netw,* May 24 2009.

[4] S. Coyle, T. E. Ward, and C. M. Markham, "Brain-computer interface using a simplified functional near-infrared spectroscopy system," *J Neural Eng,* vol. 4, pp. 219-26, Sep 2007.

[5] S. Yoo and F. Jolesz, "Functional MRI for neurofeedback: feasibility studyon a hand motor task," *Neuroreport,* vol. 13, p. 1377, 2002.

[6] S. Yoo, T. Fairneny, N. Chen, S. Choo, L. Panych, H. Park, S. Lee, and F. Jolesz, "Brain-computer interface using fMRI: spatial navigation by thoughts," *Neuroreport,* vol. 15, p. 1591, 2004.

[7] R. C. deCharms, K. Christoff, G. H. Glover, J. M. Pauly, S. Whitfield, and J. D. Gabrieli, "Learned regulation of spatially localized brain activation using real-time fMRI," *Neuroimage,* vol. 21, pp. 436-43, Jan 2004.

[8] S. Posse, D. Fitzgerald, K. Gao, U. Habel, D. Rosenberg, G. Moore, and F. Schneider, "Real-time fMRI of temporolimbic regions detects amygdala activation during single-trial self-induced sadness," *Neuroimage,* vol. 18, pp. 760-768, 2003.

[9] N. Weiskopf, K. Mathiak, S. W. Bock, F. Scharnowski, R. Veit, W. Grodd, R. Goebel, and N. Birbaumer, "Principles of a brain-computer interface (BCI) based on real-time functional magnetic resonance imaging (fMRI)," *IEEE Trans Biomed Eng,* vol. 51, pp. 966-70, Jun 2004.

[10] R. C. deCharms, F. Maeda, G. H. Glover, D. Ludlow, J. M. Pauly, D. Soneji, J. D. Gabrieli, and S. C. Mackey, "Control over brain activation and pain learned by using real-time functional MRI," *Proc Natl Acad Sci U S A,* vol. 102, pp. 18626-31, Dec 20 2005.

[11] A. Caria, R. Veit, R. Sitaram, M. Lotze, N. Weiskopf, W. Grodd, and N. Birbaumer, "Regulation of anterior insular cortex activity using real-time fMRI," *Neuroimage,* vol. 35, pp. 1238-46, Apr 15 2007.

[12] R. C. decharms, "Reading and controlling human brain activation using real-time functional magnetic resonance imaging," *Trends Cogn Sci,* vol. 11, pp. 473-81, Nov 2007.

[13] R. Sitaram, A. Caria, R. Veit, T. Gaber, G. Rota, A. Kuebler, and N. Birbaumer, "FMRI brain-computer interface: a tool for neuroscientific research and treatment," *Comput Intell Neurosci,* p. 25487, 2007.

[14] R. Sitaram, N. Weiskopf, A. Caria, R. Veit, M. Erb, and N. Birbaumer, "fMRI brain-computer interfaces," *Signal Processing Magazine, IEEE,* vol. 25, pp. 95-106, 2007.

[15] S. Yoo, J. Lee, H. O'Leary, L. Panych, and F. Jolesz, "Neurofeedback fMRI mediated learning and consolidation of regional brain activation during motor imagery," *International journal of imaging systems and technology,* vol. 18, pp. 69-78, 2008.

[16] J.-H. Lee, J. Ryu, F. A. Jolesz, Z.-H. Cho, and S.-S. Yoo, "Brain-machine interface via real-time fMRI: Preliminary study on thought-controlled robotic arm," *Neurosci Lett,* vol. 450, pp. 1-6, 2009.

[17] G. Rota, R. Sitaram, R. Veit, M. Erb, N. Weiskopf, G. Dogil, and N. Birbaumer, "Self-regulation of regional cortical activity using real-time fMRI: the right inferior frontal gyrus and linguistic processing," *Hum Brain Mapp,* vol. 30, pp. 1605-14, May 2009.

[18] B. Chance, Z. Zhuang, C. UnAh, C. Alter, and L. Lipton, "Cognition-activated low-frequency modulation of light absorption in human brain," *Proc Natl Acad Sci U S A,* vol. 90, pp. 3770-4, Apr 15 1993.

[19] A. Villringer and B. Chance, "Non-invasive optical spectroscopy and imaging of human brain function," *Trends Neurosci,* vol. 20, pp. 435-42, Oct 1997.

[20] H. Ayaz, M. Izzetoglu, P. A. Shewokis, and B. Onaral, "Sliding-window Motion Artifact Rejection for Functional Near-Infrared Spectroscopy," *Conf Proc IEEE Eng Med Biol Soc,* pp. 6567-70, 2010.

[21] A. F. Abdelnour and T. Huppert, "Real-time imaging of human brain function by near-infrared spectroscopy using an adaptive general linear model," *Neuroimage,* vol. 46, pp. 133-143, 2009.

[22] R. Sitaram, H. Zhang, C. Guan, M. Thulasidas, Y. Hoshi, A. Ishikawa, K. Shimizu, and N. Birbaumer, "Temporal classification of multichannel near-infrared spectroscopy signals of motor imagery for developing a brain-computer interface," *NeuroImage,* vol. 34, pp. 1416-1427, 2007.

[23] K. Izzetoglu, S. Bunce, B. Onaral, K. Pourrezaei, and B. Chance, "Functional Optical Brain Imaging Using Near-Infrared During Cognitive Tasks," *International Journal of Human-Computer Interaction,* vol. 17, pp. 211-227, 2004.

[24] H. Ayaz, P. A. Shewokis, S. Bunce, K. Izzetoglu, B. Willems, and B. Onaral, "Optical brain monitoring for operator training and mental workload assessment," *Neuroimage* doi:10.1016 / j.neuroimage.2011.06.023 2011.

[25] H. Ayaz, M. Izzetoglu, S. Bunce, T. Heiman-Patterson, and B. Onaral, "Detecting cognitive activity related hemodynamic signal for brain computer interface using functional near infrared spectroscopy," *Conf Proc 3rd IEEE/EMBS on Neural Eng,* pp. 342-345, 2007.

[26] G. Bauernfeind, R. Leeb, S. C. Wriessnegger, and G. Pfurtscheller, "Development, set-up and first results for a one-channel near-infrared spectroscopy system," *Biomed Tech (Berl),* vol. 53, pp. 36-43, 2008.

[27] T. Limongi, G. D. Sante, M. Ferrari, and V. Quaresima, "Detecting Mental Calculation Related Frontal Cortex Oxygenation Changes for Brain Computer Interface Using Multi-Channel Functional Near Infrared Topography," *International Journal of Bioelectromagnetism,* vol. 11, pp. 86-90, 2009.

[28] S. Power, T. Falk, and T. Chau, "Classification of prefrontal activity due to mental arithmetic and music imagery," *J Neural Eng,* vol. 7, p. 026002, 2010.

[29] S. Luu and T. Chau, "Decoding subjective preference from single-trial near-infrared spectroscopy signals," *J Neural Eng,* vol. 6, p. 16003, Feb 2009.

[30] H. Ayaz, P. Shewokis, S. Bunce, M. Schultheis, and B. Onaral, "Assessment of Cognitive Neural Correlates for a Functional Near Infrared-Based Brain Computer Interface System," in *Foundations of Augmented Cognition. Neuroergonomics and Operational Neuroscience*, ed, 2009, pp. 699-708.

[31] H. Ayaz, "Functional Near Infrared Spectroscopy based Brain Computer Interface," PhD Thesis, School of Biomedical Engineering, Science & Health Systems, Drexel University, Philadelphia, PA, 2010.

[32] H. Ayaz, S. L. Allen, S. M. Platek, and B. Onaral, "Maze Suite 1.0: a complete set of tools to prepare, present, and analyze navigational and spatial cognitive neuroscience experiments," *Behav Res Methods,* vol. 40, pp. 353-9, Feb 2008.

[33] H. Ayaz, P. A. Shewokis, A. Curtin, M. Izzetoglu, K. Izzetoglu, and B. Onaral, "Using MazeSuite and Functional Near Infrared Spectroscopy to study learning in spatial navigation," *J Vis Exp,* doi: 10.3791/3443 (In Press) 2011.

[34] H. Ayaz, M. Izzetoglu, S. M. Platek, S. Bunce, K. Izzetoglu, K. Pourrezaei, and B. Onaral, "Registering fNIR data to brain surface image using MRI templates," *Conf Proc IEEE Eng Med Biol Soc,* pp. 2671-4, 2006.