Implanted rechargeable electroencephalography (EEG) device

Xing Qian, Hongwei Hao, Bozhi Ma, Xiongwei Wen, Chunhua Hu and Luming Li

Electroencephalography (EEG) and deep brain stimulation (DBS), as specific instrument and tool, respectively, for reading and changing the electrical activities of the human brain, are milestones in the history of neuroscience and brain research. Although scientists have gone very far in exploring the brain, the mechanisms of many neurological diseases and therapies are not clear yet. Therefore, an implanted rechargeable EEG device, adding the recording function to conventional DBS to make it not only a therapy device but a scientific research tool has been developed. The EEG performance of the device is good compared with the SynAmps2 of NeuroScan. Radio-frequency (RF) communication at 403 MHz is used for data transmission, which has a high speed and long transmission distance and enables mass quantity data transmission. A rechargeable battery is used for power supply, making the system life longer and lowering the requirement of low-power design. This device is a good platform for neuroscience research by being implanted in animal models of different nervous system disorders or patients with diseases such as Parkinson's disease (PD). The recorded data will help to better understand the brain and the mechanisms of brain disorders and also help to optimise clinical therapy.

Introduction: With Europe and the United States having announced the Human Brain Project in 2013, brain research has become a global focus [1]. The ultimate reasons include the increase in brain disorders and neural diseases caused by the aged tendency of population. The therapy of deep brain stimulation (DBS) has been proven to be effective treatments for these nerve diseases, like Parkinson's disease (PD), dystonia and so on, despite the unclear mechanism of action. As one of the oldest and most widely used methods, electroencephalography (EEG) is an important tool for the investigation of the electric activity of the brain because of its high temporal resolution [2]. Most of all, electrical events at deeper locations can be explored by inserting the electrodes into the brain to record the local field potential (LFP; also known as micro-, depth or intracranial EEG). However, intra-operative LFP recording cannot be prolonged due to the risk of infection [3]. Therefore, developing an implantable EEG device is necessary for long-term recording, which will provide a platform for the study of brain diseases and for the realisation of closed-loop DBS therapy.

This Letter presents the design of a novel implantable EEG device based on many years' foundation on developing the DBS device, providing not only a therapy device but a scientific research tool. The first regulations the design should comply with are that the added circuits should not impact the existing electrical stimulating circuits, such as bringing about extra leakage current, and the stimulus artefact should not saturate the input range of the analogue-to-digital (AD) converter or the common-mode input range. Moreover the conflict between the low-power design and the large amount of data transmission should also be considered. Activa PC + S, proposed by Medtronic, which has passed the European CE certification, enables the function of recording EEG during stimulation. However, its recording data should be read out at a very close range, just several centimetres [4], which restricts at big datas output and the possibility of continuous recording and simultaneous data output. Furthermore, it is powered from a disposable lithium battery, therefore the added sensing module will relatively reduce the lifetime of the system. The implanted EEG device in this Letter is rechargeable, which will not limit the recording performance constrained by the low-power design. Radio-frequency (RF) communication at 403 MHz is used for data transmission, which has a high speed and long transmission distance, giving the patient more freedom. In addition, the function of the wireless software update gives the opportunity for the closed-loop algorithm upgrade.

Implementation of prototype: The system consists of two parts: internal and external, as shown in Fig. 1. The structure of the internal part is the same as the brain pacemaker. This part includes the deep or subdural leads, the processor which receives or delivers signals to the leads and communicates with the external part bi-directionally, and the extension wires to connect the two above. Actually the internal part can be regarded as a novel brain pacemaker with an added function of recording the brain activity. The recorded LFP or electrocorticogram (ECoG) signals can be read out by the Medical Implant Communication Service (MICS) frequency band at 403 MHz. The external part contains a receiver to receive the RF signals and a computer installed with data processing software. There is also a charger to recharge the internal lithium battery, and the previous external program controller which is still compatible with the therapy module.

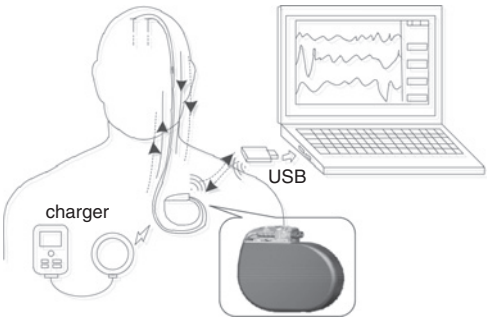

Fig. 1 *Application example and system partition for prototype*

The main electrical device architecture of the system is shown in Fig. 2 and the main characteristics of the system are listed in Table 1. Eight channels of signal can be collected from any combination of two electrodes from each lead. With the electrode configuration method referred to in [5] and the passive filter network, stimulus signal of high amplitude (up to 10 V) can be suppressed to just several hundred microvolts, and high common-mode rejection ratio (CMRR) can further greatly inhibit the stimulus signal as a common-mode signal. The recorded signals are transferred outside through a 403 MHz helical antenna put inside the header outside the titanium case.

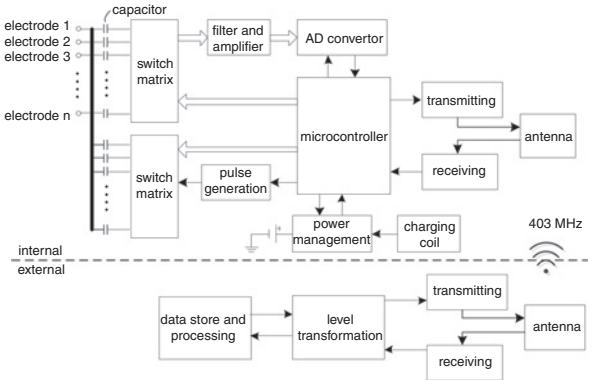

Fig. 2 *Main electrical device architecture*

Table 1: Main characteristics of implanted EEG device

LFP/ECoG recordings		Weights	<60 g
Power dissipation	<750 μW/channel	Data transmission	
Channels	8	carrier frequency	403 MHz
AD resolution	24 bit	modulation mode	2-GFSK
Sample rate	250 sps, 500 sps	transmission range	>2 m
CMRR	−115 dB	data rate	250 kbit/s
DC input impedance	1 GΩ	Stimulation	
Input-referred noise	0.4 μV_{rms}	channels	eight for bilateral (4/lead)
Lowpass corner	100 Hz (−3 dB)	pulse frequency	2–250 Hz, adjustable
Highpass corner	0.2 Hz (−3 dB)	pulse width	30–450 μs, adjustable
Input range	>+/−10 V (stimulation compliance)	pulse amplitude	voltage mode: 0–10 V current mode: 0–25 mA
Dimension of implant part		Other features	
Diameter	55 mm	rechargeable	
Thickness	11 mm	wireless software upgrading	

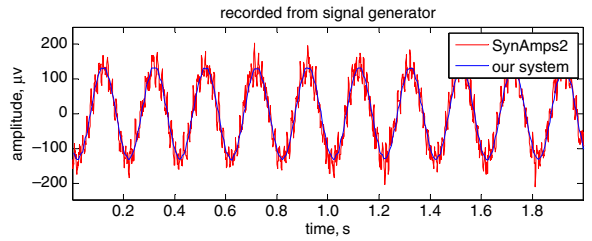

Fig. 3 *Raw waveforms recorded from signal generator*

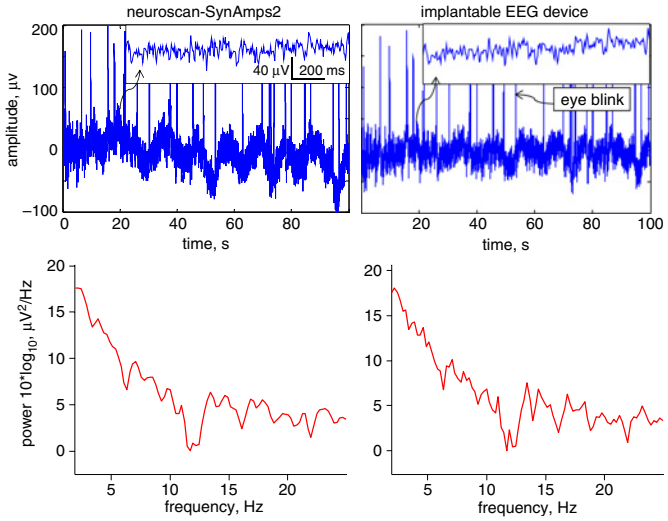

Fig. 4 *Synchronously acquired time-domain raw waveforms and spectrums of two systems*

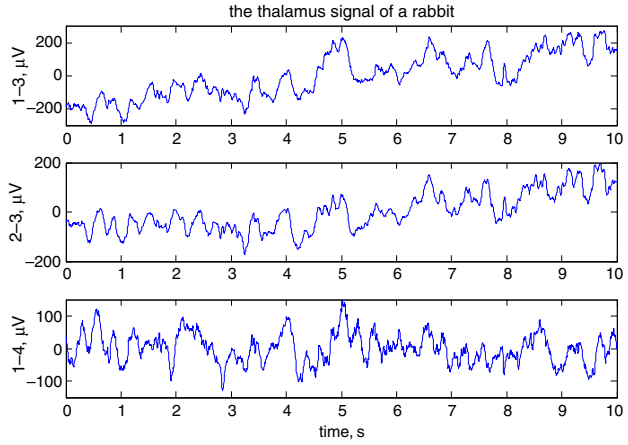

Fig. 5 *Thalamus signal of rabbit*

Top, middle and lower one, respectively, are signals between electrodes 1 and 3, 2 and 3 and 1 and 4

Validation of the implanted EEG device: Since there are no volume and power constraints, commercial EEG amplifiers often have good electrical performance, such as the SynAmps2 of NeuroScan, which is often used to obtain the event-related potential. We first validated the EEG performance using the method of recording a 5 Hz sine wave from a signal generator. Fig. 3 shows that the signal recorded by our system is smoother with less power–frequency interference. Then we compared the human scalp EEGs recorded by the two systems. The two signals are acquired synchronously at the same electrode location, which is the frontal position with the mastoid as the reference. Fig. 4 shows the raw waveforms with mixed ocular artefacts and their spectrums (2–25 Hz). The correlation coefficient of the two fast Fourier transform-transformed signals is 0.86 ($p < 0.01$). The comparison showed that the two signals are almost identical in the time and frequency domains and the performance of an our system could be compared with the SynAmps2. We also conducted an *in vivo* experiment on an awake rabbit. The thalamus signal recorded through a DBS lead (PINS, L301) and read by the RF communication is shown in Fig. 5. All experimental procedures were approved by the University Committee on Research Practice of the Tsinghua University and the NIH guide for the Care and Use of Laboratory animals [6] was strictly followed.

Conclusion: An implanted rechargeable EEG device is presented in this Letter. This device can be used for neuroscience research by being implanted in animal models for different nervous system disorders. It can also be used for patients with diseases such as PD. The recorded data read out by RF communication will help to better understand the brain and the mechanisms of brain disorders and also help to optimise clinical therapy.

Acknowledgments: This work was supported by the National Natural Science Foundation of China (51125028) and the Tsinghua University Initiative Scientific Research Program.

18 May 2014
doi: 10.1049/el.2014.1820
One or more of the Figures in this Letter are available in colour online.

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