Journal of Neuroscience Methods 233 (2014) 155–165

Contents lists available at ScienceDirect

Journal of Neuroscience Methods

journal homepage: www.elsevier.com/locate/jneumeth

Basic Neuroscience

An electrocorticographic electrode array for simultaneous recording from medial, lateral, and intrasulcal surface of the cortex in macaque monkeys

Makoto Fukushima[a,*], Richard C. Saunders[a], Matthew Mullarkey[a], Alexandra M. Doyle[a], Mortimer Mishkin[a], Naotaka Fujii[b]

[a] Laboratory of Neuropsychology, National Institute of Mental Health, National Institutes of Health, 49 Convent Drive, Bethesda, MD 20892, USA
[b] Laboratory for Adaptive Intelligence Brain Science Institute, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

HIGHLIGHTS

- ECoG array for recording from multiple gyral and intrasulcul cortical areas simultaneously.
- Compartmental design of the array allowed flexibility in implantation procedure.
- The array detected robust auditory and visual evoked potentials in an awake monkey.

ARTICLE INFO

Article history:
Received 25 February 2014
Received in revised form 10 June 2014
Accepted 17 June 2014
Available online 24 June 2014

Keywords:
Electrocorticography
ECoG
Electrophysiology
Evoked potentials
Multielectrode
Monkey

ABSTRACT

Background: Electrocorticography (ECoG) permits recording electrical field potentials with high spatiotemporal resolution over a large part of the cerebral cortex. Application of chronically implanted ECoG arrays in animal models provides an opportunity to investigate global spatiotemporal neural patterns and functional connectivity systematically under various experimental conditions. Although ECoG is conventionally used to cover the gyral cortical surface, recent studies have shown the feasibility of intrasulcal ECoG recordings in macaque monkeys.
New method: Here we developed a new ECoG array to record neural activity simultaneously from much of the medial and lateral cortical surface of a single hemisphere, together with the supratemporal plane (STP) of the lateral sulcus in macaque monkeys. The ECoG array consisted of 256 electrodes for bipolar recording at 128 sites.
Results: We successfully implanted the ECoG array in the left hemisphere of three rhesus monkeys. The electrodes in the auditory and visual cortex detected robust event related potentials to auditory and visual stimuli, respectively. Bipolar recording from adjacent electrode pairs effectively eliminated chewing artifacts evident in monopolar recording, demonstrating the advantage of using the ECoG array under conditions that generate significant movement artifacts.
Comparison with existing methods: Compared with bipolar ECoG arrays previously developed for macaque monkeys, this array significantly expands the number of cortical target areas in gyral and intralsulcal cortex.
Conclusions: This new ECoG array provides an opportunity to investigate global network interactions among gyral and intrasulcal cortical areas.

1. Introduction

The primate brain consists of multiple distinct cortical circuits underlying sensory, cognitive, and motor functions. For example, the ventral and dorsal visual cortical streams process stimulus quality and spatial location, respectively (Ungerleider and Mishkin, 1982). In audition, stimulus quality and location are also processed separately along a ventral and dorsal stream respectively (Romanski et al., 1999). In each pair of auditory and visual streams,

* Corresponding author at: Laboratory of Neuropsychology, National Institute of Mental Health, National Institutes of Health, Building 49, Room 1B80, 49 Convent Drive, Bethesda, MD 20892, USA. Tel.: +1 301 443 7458; fax: +1 301 402 0046.
E-mail address: makoto.fukushima@me.com (M. Fukushima).

http://dx.doi.org/10.1016/j.jneumeth.2014.06.022
0165-0270/Published by Elsevier B.V.

response latency increases from the primary to the higher-order sensory areas (Raiguel et al., 1989; Schmolesky et al., 1998; Bendor and Wang, 2008; Kikuchi et al., 2010; Scott et al., 2011). Although this suggests that the sensory information is processed serially, the cortical subdivisions in these pathways are also connected reciprocally (Hackett, 2011; Kravitz et al., 2011, 2013). The exact functions served by interactions among cortical areas have not yet been fully investigated because of the considerable technical challenges in measuring and analyzing neuronal activity with high spatiotemporal resolution from multiple brain areas. Conventionally, each cortical area has been investigated individually through electrophysiological recording of spikes and local field potentials (LFPs) by penetrating cortical tissue with single or multiple microelectrodes. Although this method can capture detailed neural responses with millisecond resolution, and it has also been used for recording from multiple cortical areas simultaneously (Truccolo et al., 2011; Feingold et al., 2012; Salazar et al., 2012), it is not ideal for recording at high spatial resolution across large extents of the cortical surface. Another approach is functional MRI, but while it can probe whole brain activity noninvasively, it does so with relatively low spatial and temporal resolution.

An alternative method that combines both high spatial and high temporal resolution is Electrocorticography (ECoG), which can record neural activity simultaneously from numerous electrodes placed on the surface of the cortex without penetrating the cortical tissue with electrodes. ECoG has been used to detect epileptogenic foci by recording LFPs across a large expanse of cortex in human patients (Palmini, 2006). Also, because ECoG allows extensive coverage of the cortex, it recently has become an important experimental tool for investigating functional interactions among cortical areas underlying various sensory, motor, and cognitive functions (Canolty and Knight, 2010; Beauchamp et al., 2012; Mesgarani and Chang, 2012; Chang et al., 2013). There has also been increasing interest in applying ECoG to record information carried in different temporal scales e.g. gamma and theta band oscillations (Fries, 2005; Edwards et al., 2009; Schroeder and Lakatos, 2009; Viventi et al., 2011; Giraud and Poeppel, 2012; Einevoll et al., 2013). These applications of ECoG have been made possible by recent advances in high-channel-count data acquisition and mathematical tools for analyzing high-dimensional data (Brovelli et al., 2004; Bressler and Seth, 2011; Friston et al., 2012). Further, application of chronically implanted ECoG arrays in animal models provides an opportunity to investigate global spatiotemporal neural patterns and interactions systematically under various experimental conditions (Rubehn et al., 2009; Chao et al., 2010; Bosman et al., 2012).

ECoG is applicable for recording LFPs not only from the cortical surface of a gyrus but also from the cortex buried within sulci (Yanagisawa et al., 2009; Matsuo et al., 2011; Fukushima et al., 2012). For example, major proportions of the auditory cortex in humans and macaques are imbedded in the lateral sulcus (Formisano et al., 2003; Hackett, 2011). We recently developed a technique for inserting ECoG arrays into the lateral sulcus to allow recording simultaneously from primary and higher-order auditory subdivisions located on the supratemporal plane (STP) (Fukushima et al., 2012, 2014). In the current study, we combined this technique with another technique developed for an ECoG array that was designed to cover the lateral and medial gyral surfaces of the macaque cortex (Nagasaka et al., 2011).

2. Material and methods

2.1. Electrode manufacturing process

The ECoG array was manufactured and assembled by Cirtech Inc. (Shizuoka, Japan) with microelectromechanical system (MEMS) technologies (Fig. 1). The base of the array, made of a thin, flexible, circuit board material (FELIOS, RF786W 54ET-M, Panasonic Corp., Osaka, Japan), consisted of a layer of polyimide film sandwiched between two copper layers (Fig. 1b). First, holes (0.1 mm diameter) were made with laser drilling (Model 5330, Electro scientific industries, OR, USA) at the desired locations for electrode contacts in the base material. Then the holes were copper-plated to establish electrical continuity between the copper layers. With dry etching, the copper layer on one side was shaped for electrode contacts, and the copper layer on the other side was shaped for wiring the electrode to the connector. The copper layer for wiring was insulated by covering it with a polyimide film attached with glue (CISF0515 2NKF, Nikkan industries Co. Ltd., Tokyo, Japan). Finally, all the electrode contacts were gold-plated.

2.2. Electrode layout and design

Each recording site was a circular disk with a diameter of 0.8 mm, and the distance between two sites in a bipolar pair was 1.8 mm (Fig. 2a). The full complement of the ECoG array consisted of four compartments, each of which was attached to a separate connector (Fig. 2b). This provided flexibility in implanting one of the compartments in the lateral sulcus (see implantation procedure). Each of the four array compartments has 56–70 recording sites soldered to a narrow-pitch connector (Fig. 3a and b, F4S, AXT5E6026 for 60 channels or AXT5E7026 for 70 channels, Panasonic Corp., Osaka, Japan). The connector enclosure is made of peek resin (Fig. 3b and c).

The 'finger' electrode strips extended dorsoventrally or caudorostrally (e.g. compartments #1 and #3, respectively, in Fig. 2b), similar to those in an ECoG array developed previously (Rubehn et al., 2009). Although this finger design was an appropriate fit for most of the electrodes on the frontal and parietal lobes, we found it difficult to place the electrodes on the posterior part of the occipital lobe without each electrode overlapping another, mainly due to the extreme curvature at the occipital pole in both dorsoventral and caudorostral directions. Because this pole could be approximately modeled as part of a sphere, we designed a fan-shaped electrode array (compartment #2, Fig. 2b), which fit tightly to the spherical curvature of the pole (Fig. 6a)

2.3. Impedance measurement

Impedances of all 256 sites in the ECoG array were measured at Unique Medical Co. Ltd. (Tokyo, Japan). The array, together with a gold reference electrode, was placed in 0.9% saline solution at room temperature. The electrode was serially connected to a resistor with known resistance values (1 kΩ for 10 and 100 Hz and 1 MΩ for 1 and 10 kHz, R_0 in Fig. 4a), to form a simple voltage divider circuit (Fig. 4a). Sinusoidally modulated voltage with 0.1 mV RMS (V_{in} in Fig. 4a) was applied through a signal generator (AG-203 CR oscillator, Kenwood, Tokyo, Japan). Then the output voltage (V_{out} in Fig. 4a) was measured with an analog voltage meter (Kikusui Electronics Corp., Kanagawa, Japan) coupled with a high input impedance amplifier (>1 GΩ, Unique Medical Co. Ltd., Tokyo, Japan) to calculate the impedance value of each of the 256 electrodes.

2.4. Subjects

We used three adult male rhesus monkeys (*Macaca mulatta*), weighing 5–10 kg. All procedures and animal care were conducted in accordance with the Institute of Laboratory Animal Resources Guide for the Care and Use of Laboratory Animals, and all experimental procedures were approved by the National Institute of Mental Health Animal Care and Use Committee.