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An acute method for multielectrode recording from the interior of sulci and other deep brain areas

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Abstract

Most current techniques for multielectrode recording involve chronically implanting planar or staggered arrays of electrodes. Such chronic implants are suited for studying a stable population of neurons over long periods of time but exploratory studies of the physiological properties of cortical subdivisions require the ability to sample multiple neural populations. This makes it necessary to penetrate frequently with small multielectrode assemblies. Some commercial systems allow daily penetrations with multiple electrodes, but they tend to be bulky, complex and expensive, and some make no provision for piercing the barrier of fibrous tissue that often covers the brain surface. We describe an apparatus for inserting bundles of 3–16 electrodes on a daily basis, thus allowing different neural populations to be sampled. The system is designed to allow penetration through a thick dura mater into deep brain structures. We discuss a simple method for performing multielectrode recording from cortical areas buried inside sulci using acute implantations of a bundle of electrodes. Our results show that it is possible to obtain stable recordings for at least 4 h and that repeated implantations yield an average of two neurons per electrode with every electrode in the bundle picking up at least one single neuron in 70% of the implantations.

Keywords: Middle temporal area; Superior temporal sulcus; Multielectrode array; Gliosis

1. Introduction

Extensive electrophysiological studies of single neurons for more than 40 years have accumulated detailed knowledge about the functional subdivisions of the cortex, the specialized functions of different types of neurons within each subdivision, and the relationship of single neuron response to behavior (rev. Albright et al., 2000). The focus is now shifting to the study of emergent properties of collective responses of neural populations, spatiotemporal interactions between neurons and the relationship of neural population response to behavior (rev. Erickson, 2001). Consequently a number of successful multielectrode recording methods that allow the simultaneous measurement of the responses of dozens of neurons have emerged (Nicolelis and Ribeiro, 2000; Wise et al., 2004; Rousche and Normann, 1998). The most popular and productive among these methods consist in surgically implanting chronic multielectrode arrays. Over the past decade, these methods have been greatly improved, allowing for interaction with a fairly stable population of a large number of neurons (>100) for long periods of time. This has enabled studies of learning, population response correlates of behavior and prosthesis.

Most multielectrode arrays used in these studies are designed as planar or staggered 3-D arrays that are suited for surface or subsurface implantations but not for recording from the interior of sulci or other deep brain areas. But many cortical areas that underlie critical behavioral and sensory functions lie buried inside sulci. For example, in the visual system of rhesus monkeys, the middle temporal area (MT) that lies on the posterior bank and the floor of the superior temporal sulcus (STS) is highly specialized to analyze motion (Dubner and Zeki, 1971; Zeki, 1974). Extensive studies of MT with single electrodes have revealed that single MT neurons preferentially respond to a given direction of motion and often to a given range of speeds (Maunsell and Van Essen, 1983a; Lagae et al., 1993) and disparities (Maunsell and Van Essen, 1983b). Studies have also linked the responses of single MT neurons to perceived

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direction and disparity (rev. Britten, 2004). Many current studies are focused on understanding whether the collective responses of populations of MT neurons exhibit emergent properties that cannot be directly inferred from the responses of single neurons (Lisberger and Movshon, 1999). The relationship of such population responses to behavior has also not been studied in detail. Therefore, multielectrode recording from the posterior bank and the floor of the STS will yield valuable information.

Though planar and 3-D microelectrode arrays are not suited for such recording, microwire bundle and microwire arrays are an exception and could be used to study cortical areas buried inside sulci as well as midbrain structures embedded well inside the neocortex. But a chronic bundle or array makes contact with almost the same population of neurons during its entire lifetime, depending on the stability of the tissue–electrode interface. Such an arrangement is suited for exploring the long-term changes that occur in neural assemblies through learning and for developing prosthetic devices. But studies of functional properties of a physiologically or anatomically well-defined cortical area require an active exploration of the entire area to gain an understanding of all the functionally and physiologically distinct types of neural populations that constitute the area, the statistical distribution of their properties, the interactions between the different types of neural populations and the relationship of the responses of the different neural populations to behavior. Such an exploration requires that the electrodes be maneuverable through the cortical area of interest.

Many available techniques for implanting multielectrode arrays and bundles offer limited maneuverability. This inability stems from two factors. First, the arrays and bundles have to be surgically implanted as chronic devices and their designs often do not allow for the displacement of the electrodes after implantation. Second, chronically implanted electrodes, irrespective of the material they are made from or coated with, suffer from cellular encapsulation due to reactive gliosis characterized by the hypertrophy of astrocytes. Capsules of 100–200 μm widths are known to form around most materials, such as silicon, stainless steel, tungsten, platinum–iridium-coated metal and teflon-coated metal, within 24 h of implantation (Agnew et al., 1986; Norton et al., 1992; Yuen and Agnew, 1995; Turner et al., 1999; Szarowski et al., 2003). Hence any attempt to displace chronically implanted electrodes will likely detach the cellular capsule from the cortex and drag it along with the electrodes, resulting in undue damage to the cortex.

While many available techniques that use multielectrode or multiwire arrays and bundles do not allow for maneuvering the electrodes, some commercially available systems allow daily penetrations with up to 16 individually maneuverable electrodes. An excellent example of such a system is the Eckhorn or Thomas drive (Eckhorn and Thomas, 1993; available from Thomas Recording GmbH). Since these systems are designed to individually advance each electrode, they are expensive and sometimes require difficult manual adjustments of the individual electrodes (Baker et al., 1999).

We have tested a simple, inexpensive and robust alternative that allows many repetitive acute implantations (>150) of multielectrode bundles in the same cortical area over long periods of time (>2 years), yields up to a dozen or more neurons for each implantation, minimizes cortical damage due to dimpling and cellular encapsulation, and demonstrates good signal-to-noise ratio (SNR) and isolation of action potentials. The acute penetrations prevent the reactive gliosis process from forming significant cellular capsules. Each implantation can be adjusted to sample a new population of neurons. Thus both requirements outlined above are satisfied by this method. These advantages were achievable because we compromised on the individual maneuvering of each electrode in the bundle and instead relied on a simple "poke and hope" method that, as we describe below, has proven surprisingly successful. Here we describe a set of design principles and a repertoire of practical dos and don'ts that constitute this technique.

2. Methods and materials

2.1. Design constraints

We identified four critical properties that our design must impart to the multielectrode bundle: (1) a desired minimum spacing between the electrode tips, (2) alignment of the electrode tips to within a desired tolerance level, (3) ability to minimize or prevent the tendency of the electrodes to splay-out as the bundle moves through the cortex and (4) ability to minimize or prevent the tendency of the bundle to dimple the cortex instead of penetrating it.

We now briefly discuss these four requirements. Most sensory areas of the neocortex have a columnar organization, with a column being a single iteration of a local neural circuit repetitively realized in the entire neighbourhood (Mountcastle, 1997). The pattern of connectivity between the columns sets up a distributed neural assembly that underlies a distributed function. Most multielectrode studies of neural assemblies focus on understanding the properties of this distributed system. Therefore, it will be productive to space the electrodes so that no two electrodes sample the same cortical column. The size of cortical columns varies from 200 to 600 μm depending upon the cortical area and the species (Mountcastle, 1997). In our studies of area MT in rhesus monkeys, we required that the spacing between any two electrodes be at least 200 μm, which is very likely to result in different electrodes sampling neurons with different preferred directions (Albright et al., 1984). Though our design is specific to this number, it is easy to choose the components of the bundle to achieve any required spacing as explained below.

Second, the requirement for the alignment of the electrode tips will also vary depending on the study, but it is of two broad categories: (1) all electrodes should be preferably placed in the same cortical layer or (2) they should span all the cortical layers. If the penetration is perpendicular to the cortical surface, then the first requirement can be achieved by aligning all the electrode tips to be within 100 μm of each other. If the electrodes need to span the different cortical layers, then the tips can be staggered appropriately. But if the penetration is oblique to the cortical surface, then the electrode tips will need to be precisely staggered depending upon the geometry of the recording site.