A MULTI-CHANNEL, IMPLANTABLE MICRODRIVE SYSTEM FOR USE WITH SHARP, ULTRA-FINE "REITBOECK" MICROELECTRODES

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ABSTRACT

Arrays of closely spaced quartz insulated, platinum-tungsten microelectrodes (Reitboeck, 1983a) are widely used to obtain acute recordings from chronically prepared subjects. These electrodes have excellent recording characteristics, and can be fabricated to a wide variety of tip specifications. Typically, in such experiments, electrodes are introduced into, and removed from the brain on a daily basis and, over many months of study, hundreds of penetrations may be made through an intact dura. This procedure has benefits as well as problems and risks. For some experimental aims it might be desirable to leave the microelectrodes within the brain so that the penetrations could be continued on subsequent days. This would allow a more thorough and systematic exploration of the neurons that lie along the trajectory of each of the closely aligned electrodes and would minimize risks and preparation time associated with daily electrode insertions. Here we present a means for achieving this aim using arrays of sharp, flexible Reitboeck electrodes of extremely fine diameter (40 micron shaft diameter, pulled and ground to a fine tip). We show that these electrodes retain their excellent recording characteristics and can remain under microdrive control within the brain for periods of many months and, in one remarkable case, for more than four years.
INTRODUCTION

It is now commonplace for acute electrophysiological experiments to be conducted on chronically prepared subjects for periods of many months. In some such experiments the aim is to record simultaneously from groups of well-isolated single neurons, and closely spaced arrays of independently controlled “Reitboeck” electrodes (Reitboeck, 1983a), have proved to be especially well suited for such aims (e.g., Alonso et al., 2001; Baker et al, 1999; DiCarlo et al., 1998; Eckhorn et al., 1988; Gail et al., 2004; Lee, 2004; Lee et al., 1998; Mountcastle et al., 1991; Steinmetz et al., 2000; Swadlow and Gusev, 2001; 2002; Usrey et al., 2000). These electrodes are fabricated from filaments consisting of a platinum-alloy core (platinum 90%, tungsten 10%) and an insulating shell made of quartz. Because the metal alloy core and the quartz insulation have similar melting points and expansion coefficients, these filaments can be pulled under high temperature to a fine taper. The tips are then ground to the desired characteristics. The fine and consistent outer diameters of these filaments (commercially available at 80, 60 and 40 microns, Thomas Recording Co., Giessen, Germany), allows them to be fit into guide tubes that direct them to a very small area of brain tissue, and the stiffness of these filaments generates a predictable electrode trajectory. To manipulate these fine-diameter electrodes, microdrive systems have been developed that allow independent control of each electrode while preventing buckling of the portion of the narrow shafts that lie above the guide tubes (Reitboeck, 1983a,b; Eckhorn and Thomas, 1993, see reviews by Mountcastle et. al., 1991, and Baker et. al., 1999). These methods require the electrodes to be inserted into the brain (usually through the dura) at the beginning of each recording session, manipulated by the external microdrives, and removed at the end of a recording session.
For some experimental aims, however, it would be desirable to leave electrodes within the brain for longer periods, and to slowly explore each of the single neurons that lie along several closely spaced microelectrode penetrations. In principal, Reitboeck electrodes are well suited for chronic indwelling use because both the platinum alloy core and the quartz shell are very durable and stable materials. Here, we describe a system for utilizing densely packed, indwelling arrays of independently controlled Reitboeck electrodes for long-term, chronic recording. We describe (1) a compact and simple method for preventing the buckling of these electrodes that is suitable for use with electrode shaft diameters as small as 40 microns, (2) an ultra-miniature, multiple microdrive system that allows the independent control of these electrodes, and (3) procedures for keeping electrodes mobile and under microdrive control for many months by minimizing the entrance and subsequent coagulation of brain fluids within the guide tubes. We have used variants of this system in rabbits for more than five years. Electrodes typically remain mobile, under microdrive control, and able to record from well-isolated single neurons for periods of many months and, in once case, for more than four years.

METHODS

The methods below were developed to accommodate Reitboeck electrodes constructed of filaments of 40 micron outer diameter (metallic core of 14 microns, Thomas Recording Co.), but can be scaled up to accommodate the larger filaments (80 micron outer diameter) as well. These electrodes are pulled to a fine taper in a high-temperature (~ 2100° C) vertical puller (Thomas Recording Company). This is done within a chamber that is filled with inert gas to prevent oxidization of the tungsten filament. The tips are then sharpened to the desired characteristics
using a fine diamond grinding wheel\(^1\). Methods for fabricating these electrodes have been described by Reitboeck (1983a). The system described below has been used to control seven such electrodes within the cortex, thalamus, or superior colliculus of the rabbit (Bezdudnaya et al., 2003, Cano et al., 2003; Swadlow and Gusev, 2000, 2001; 2002). Figure 1A shows a photograph of a completed 7-channel system with a single electrode in place within the left-most guide tube.

**The microelectrode and the “buckling” problem.** A primary problem impeding the using of these fine filament electrodes is that the shaft readily “buckles” when the tip encounters any resistance (e.g., the dura, see discussion in Eckhorn and Thomas, 1993; Reitboeck, 1983b). The portion of an electrode located within a guide tube is, of course, constrained, but the electrode shaft lying between the top of the guide tube and the point of fixation to the microdrive is susceptible to buckling. The problem, then, is to constrain this portion of the shaft while still retaining the ability to lower the electrode. The “Eckhorn” microdrive system (Eckhorn and Thomas, 1993) provides an elegant solution to the buckling problem for acute use of fine filaments. This system uses stretchable silastic tubing to both constrain buckling of the portion of the electrode that lies above the guide tube and to provide power to drive the electrode forward. This solution has advantages over the original clutch-based drive mechanism described by Reitboeck (Mountcastle et al., 1991; Reitboeck, 1983b). However, neither of these solutions are satisfactory for manipulation of chronically implanted electrodes. Moreover, very fine

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\(^1\) We grind electrode tips using a continuously wetted, “extra fine” diamond abrasive plate (Sutter Instrument Company, Novato California, plate model 104 F), that is rotating towards the electrode tip (at 1 – 3 revolutions/s) on a home-made horizontal turntable. The electrode is held within a length of stainless steel tubing at an angle (to the grinding wheel) of ~ 12 degrees. During grinding, the electrode is rotated about its axis (at ~ 0.3 revolutions/s) using a toy motor that is linked to the electrode by a rubber band. A complete grinding system is commercially available from Thomas Recording Company.
diameter filaments (40 microns or less) will often buckle and break within the silastic tubing of the Eckhorn system.

Because of the above problems, an alternative method was developed to prevent the electrode from buckling using a “tube-over-tube” principal. Here, buckling is prevented along the length of the electrode by either the stainless steel guide tube or by a second tube, attached to the top of the electrode, that fits over the guide tube. Figure 2 illustrates the steps in the construction of these electrodes. Dimensions given are suitable for use when associated guide tubes are 22 mm long and electrode travel need extend 5 mm beyond the tip of the guide-tube.

After fabrication of electrodes is complete, impedance measures are made to insure electrical continuity (generally 1 – 3 Mohm at 1000 Hz for electrodes aimed at recording from well-isolated single units). However, we have found visual inspection of the tips to be more useful than impedance measurements in predicting electrode performance.

The 7-channel guide array. The guide tube array (Fig. 1A, a) is constructed of 33 gage stainless steel tubing (I.D. = 100 microns), the walls of which have been thinned to ~25 microns (O. D., ~150 microns, special order, Small Parts Co, Miami, Fla.). Distal ends are bound together in a concentric array by tight-fitting polyimide tubing and Epoxylite insulation (heat cured) is used to secure the tubes together. The combined tips are slightly beveled and cleaned after construction is complete. Cutting and beveling of stainless steel tubing is accomplished using a small diamond grinding wheel (0.1 mm thick, Abrasive Technology, Lewis Center, Ohio). The upper portion of the guide tubes are separated and inserted through matching holes drilled into a plastic template (1A, c). Each of the guide tubes has an associated (somewhat larger) hole that
has been pre-drilled to accommodate the base of a microdrive\textsuperscript{2}. The tops of the guide tubes are indicated by the dashed arrow in Fig. 1A.

**Preventing blockage of the guide tubes.** It is crucial that fluids from the brain be prevented from entering the guide tubes. Otherwise, solidification of the fluids would soon prevent the movement of the electrodes. To deal with this problem we first fill each guide tube with a single application of a sterile antibiotic ointment (Vetropolycin, a bacitracin-neomycin-polyoxymyxin ophthalmic ointment). This is accomplished by pressure injection, until the ointment can be seen emerging from the distal ends of the tubes. Next, we create a hydrophobic seal at the tips with melted bone wax. The microelectrodes readily penetrate a few hundred microns of the bone wax, but the wax must be securely positioned and held within/over the tips of the guide tubes. Otherwise, the electrodes could displace, rather than penetrate the wax. We have used several means to achieve this. Most recently, for studies of cortex, we have secured a length of polyimide tubing over the guide tube array (using "Vetbond", a biocompatible cyanoacrylate glue) to create a space at the tips of \textasciitilde0.25 mm. After filling the guide tubes with antibiotic ointment, with the electrodes retracted within the guide tubes, the space at the tip of the guide tube is filled with melted bone wax (\textasciitilde40 nanoliters of bone wax is required to fill this space). As shown in Fig. 1B, the microelectrodes readily penetrate this amount of bone wax.

**The microdrives.** Many systems of simple, screw-driven microdrives have been developed for chronic recording purposes. To be suitable for the above electrode-guide-tube arrays, the microdrive must simply provide the appropriate linear motion along the z-axis (3-6 mm for our

\textsuperscript{2} Another means to control the position of the guide tubes is to fit them into slots that are ground into the side of the template (rather than into drilled holes). It is easier to fit the guide tubes into these slots, but the
purposes) and be narrow enough to allow one microdrive to be aligned with each guide tube without overcrowding. The requirement for such close spacing of microdrives presents a challenge. Two components are generally found in screw-driven microdrives: (1) a screw, and (2) a linked shaft assembly, located parallel to the screw, that constrains motion to a single (z) axis. In order to reduce the x-y dimensions of the microdrive so that drives could be more densely packed, this general design principle was modified and the parallel shaft assembly was eliminated. Fig. 3 is a schematic illustration of this microdrive and shows it’s basic design principle. A fine stainless steel screw (0000-160, J.I. Morris, Co., Southbridge, Mass) is housed within a cylinder (made from 22 gauge, thin-wall stainless steel tubing, Small Parts Co.) that has a nut (matching the 0000-160 screw) soldered to the top. A cross-bar is soldered to the top of the screw so that it can easily be turned. The screw is threaded through the nut, and it's distal, flattened tip pushes down on a piston which has an armature that exits the cylinder at ~ a 90 degree angle via a groove along the length of the cylinder. This groove serves to constrain the motion of the armature to a single (z) axis. The armature will later be secured to the microelectrode and will control its motion. The piston is held tightly against the base of the screw by a small compression spring that puts an upward pressure on the armature. The microdrive is light (~ 60 mg) and is narrow enough (about 1 mm diameter) so that microdrives can be spaced at distances of ~1.3 mm.

**Preparing the microdrive system for use.** Prior to use, the guide tube array is disinfected in 70% alcohol. Since liquids do not readily enter such fine tubing, the alcohol is pressure injected into each tube and then placed within the bath. After disinfection, the guide tubes are filled, by pressure injection, with the antibiotic ointment, and melted bone wax is applied to the tips of the upper ends of the guide tubes are generally more divergent when using this method.
guide tubes to create the hydrophobic seal. The electrodes are usually inserted and attached to the microdrives prior to the day of surgical implantation. Electrodes are inserted into the guide tubes under microscopic control and manually advanced until the polyimide tubing over the upper portion of the electrode passes over the stainless steel guide tube. The upper portion of the electrode (the polyimide tubing) is then secured to the microdrive armature using a small amount of melted dental impression compound (illustrated on the right side of Fig 3J). This juncture is rigid, but can be readily broken to re-position or exchange an electrode (electrodes can be exchanged either before or after the array has been implanted). The electrode is then advanced using the microdrive until the electrode tip is observed to emerge from the bone wax at the tip of the guide tubes. The electrode is then retracted a known distance (one or two hundred microns) into the bone wax. This procedure is repeated for each of the seven electrodes. The electrodes can also be placed into the guide tubes after the array has been surgically fixed into position, but the position of the electrode tips are less accurately known when using this procedure.

**Implanting the array and fixing it to the skull.** The array is mounted on a stainless steel rod that can be held by a stereotaxic carrier. The rod has a break-point near the junction with the array, so that it can be released after being cemented to the skull. For cortical recordings, the bone wax at the tips of the guide tubes is placed in contact with the dura. For thalamic recordings we usually insert the guide tubes through overlying (nonrelated) cortex so that the tips lie 3 - 4 mm above the region under investigation. Antibiotic ointment is applied to the surface of the dura and the array is cemented into place using acrylic cement. This cement is applied liberally over the skull and around the guide tubes, and is joined to the cement around the head-bolt assembly to ensure stability. Further stability is achieved by creating a cement bridge that

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3 An alternative means of maintaining upward tension on the piston is through the use of a very fine band of elastic material that pulls upward on the armature and is attached to the microdrive near the nut.
joins the acrylic mass on the skull to the position on the array where the guide tubes are beginning to separate (~ 10 mm above the skull). Electrical contact between the electrodes and a miniature plug is made by soldering a length of Teflon coated Platinum-iridium wire (25 or 50 micron core diameter) to the platinum rod at the top end of each electrode. Our 7-channel microdrive system (as shown in Fig 1) generally extends 30 - 35 mm above the level of the skull. A molded plastic cap that attaches to the head bolt protects the array between recording sessions.

RESULTS

This system, or similar prototypes, has been in use for more than five years in studies of the somatosensory and visual systems of the awake rabbit. Recordings were obtained from neurons of ventrobasal thalamus (Swadlow and Gusev, 2000; 2001; 2002; Swadlow, Gusev, and Bezdudnaya, 2002), dorsal lateral geniculate nucleus (Cano et al., 2003; Bezdudnaya et al., 2003), visual and somatosensory cortices, and the superior colliculus. Fig. 4A-C shows light and electron micrographs of three of seven electrodes that had been used to record from the LGNd of one rabbit for a little more than 6 months. Importantly, six of the seven electrodes\(^4\) in this array remained mobile for this entire period. No deterioration of the tips is visible at this degree of magnification\(^5\). A final exploratory penetration within the LGNd was made one day prior to removing these electrodes from the brain using the electrode shown in 4C. Fig. 4D1 – D4 shows spikes, associated clusters, and visual receptive fields\(^6\) obtained during this final

\(^4\) One of the seven microdrives ceased to function due to an inadequate solder joint between the nut and the stainless steel tube (Fig 3).

\(^5\) The bent tip in electrode "C" is clearly the result of a mechanical accident. We do not know when this occurred but, based on the fresh appearance of the fractured quartz in the electron micrograph (Fig. 4C2), we guess is that it probably happened after these recordings were obtained, as the electrode was removed from the guide tube.

\(^6\) These receptive fields were concentrically organized and only the on-center responses are shown. The fields (and those in Fig. 7) were generated using methods of reverse correlation. Stimuli consisted of 1 or 2 degree flashing light spots, presented pseudo randomly in a spatial grid of at least 16 x 16.
penetration. It is important to note that during the six months of study, we had already lowered and raised this electrode several times within the LGNd. These finely tapered electrodes typically allowed us to record from thalamic neurons that had been previously passed by the electrode tip, often by > 1 mm.

In one remarkable rabbit, a 7-channel system was in place, with electrodes within and above VB thalamus, for a period of four years and five months. This subject was studied extensively during the initial one-year period and recordings were periodically obtained during the subsequent years. At the end of this period, three of the seven microelectrodes were still under microdrive control and were recording well. Moreover, neurons with apparently normal receptive fields were still encountered by these electrodes (i.e., most of the neurons yielded robust responses that were dominated by a single vibrissa and showed a clear preference for the direction of vibrissa displacement, e.g., Swadlow and Gusev, 2002). Fig. 5A-B shows micrographs of two of these electrodes, and Fig. 5C shows action potentials (and associated cluster analysis) that were recorded from the electrode shown in 5A. These recordings were obtained at several depths within VB thalamus, just before these electrodes were removed from the brain. Clearly, there is some deterioration of the quartz insulation that is visible near the tip. Fig. 5A2, B2 show electron micrographs of these electrode tips that show, more clearly, the deleterious effects of > four years within the brain.

To quantify this deterioration, we measured the diameter of these electrode shafts at a distance of 2 mm from the tip (where the shaft had been in contact with the brain) and at a distance of 15 mm from the tip (where the shaft had been protected within the guide tube). For both electrodes, the shaft was reduced in diameter by 4-5 microns at the distal site. This value,
and the visible characteristics of the tips, are consistent with a dissolution of the quartz insulation from the surface of the shaft at a rate of ~ 0.5 microns/year.

The rabbit described above was sacrificed at the age of 5 ¾ years, after the guide tube array had been in place for 4 years and 5 months. The rabbit was perfused with saline followed by formalin and the tissue was sectioned and stained for Nissl substance. This array was implanted a little deeper than we had planned, and the tips of the guide tubes inadvertently penetrated the dorsal thalamus (Fig 6A). Unfortunately, the preparation of this tissue was less than ideal, the plane of our tissue sections were not well-aligned with the angle of the guide tubes, and many freezing (and other) artifacts are present. Nevertheless, aside from the mechanical damage done by the guide tubes (total outer diameter of the array was ~ 0.5 mm, as in Fig. 1B), damage to tissue around the tips of the guide tubes (which had been filled with bone wax) seemed minimal. No unambiguous signs of the electrode tracks could be followed to VB thalamus (Fig. 6B), where recordings were obtained.

For cortical recordings, and for recordings from the superior colliculus (which lies about 5 mm beneath the dural surface of the rabbit), the tip of the guide tube array rested on the dural surface. Because extensive tissue reaction and growth often occurs on the dura, we were concerned that the guide tubes might be quickly blocked, with a consequent loss of electrode mobility. This occurred only very rarely. Figure 7 (top) shows receptive fields generated in superficial superior colliculus by five microelectrodes within one week after this electrode array was implanted. These electrodes were of low impedance (< 1 Mohm), designed to be optimal for multiunit and field potential recordings, as well as for microstimulation. The bottom of Fig. 7 shows the receptive fields recorded from these same electrodes just over one year later.

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7 By the end of the initial year after implantation, one of the 7 microdrives was broken and another of the electrodes was frozen within it's guide tube. By the end of the fourth year, two additional electrodes were
Receptive fields were periodically monitored during the intervening months and between these measures, the electrode tips were usually moved to a position about 1 mm above the collicular surface.

DISCUSSION

Reitboeck electrodes have a number of characteristics that make them very well suited for long-term use within the brain: (a) The platinum-tungsten alloy core has excellent recording characteristics and is virtually inert. In contrast, electrode tips made of pure tungsten (which is not inert) can degrade considerably after only a few days in the brain (Malpeli et al., 1992). (b) The quartz insulation is very tough and, relative to other glasses, is very stable. The degradation that we noted after > 4 years in the brain is consistent with a dissolution of the surface of the quartz insulation at a rate of ~ 0.5 microns/year. (c) The very fine maximal outer diameter of the Reitboeck electrodes allow them to be funneled down very fine-diameter guide tubes for very close electrode spacing, yet their stiffness generates a straight and predictable electrode trajectory.

In all of these experiments the rabbits were awake, but the head was fixed during recordings. Thus, these were not freely behaving subjects, and our experimental aims have generally been to record from well-isolated single neurons for several hours, and then to move on to record from other such neurons. Because these electrodes can be fabricated with very fine tips, they are well suited to record from neurons of all sizes. Although long-term recordings from the same neuron was not the goal of these experiments, we sometimes did record from a neuron for several days (e.g., see neuron “Hercules” in Swadlow and Gusev, 2002). Low-impedance, fixed microwires are undoubtedly better suited when it is desirable to study the same neuron for very long periods of time (e.g., Porada et al., 2000; Swadlow, 1982; 1985).
We have used different variations of this system in rabbits for more than five years, and have varied the 7-channel concentric design described here in several ways. For cortical recordings, we have employed either 3-channel triangular arrays, 7-channel concentric arrays, or 5-7 channel linear arrays of guide tubes and electrodes (most with 150 micron spacing as described above). We have also employed 19-channel\(^8\) concentric arrays of guide tubes and electrodes for recording both from the thalamus and from the superior colliculus. Somewhat longer guide tubes (27 – 30 mm) are required for such large arrays to allow adequate spacing for the microdrives.

In order to prevent fluids from entering and solidifying within the guide tubes, we used small quantity of bone wax to create a hydrophobic seal at the tip of the guide tube. In our initial studies, we sealed the tips of the guide tubes so that a small amount of hot bone wax entered the tubes. In later studies we expanded this hydrophobic seal by creating a wax-filled chamber, containing about 40 nanoliters of bone wax, at the tips of the guide tubes (as in Fig. 1B). Whereas bone wax is relatively biocompatible, there are some reports of long-term effects of this substance (Aksu et al., 2001; Alberius et al., 1987; Allison, 1994). Moreover, bone wax is resorbed, albeit very slowly. Undoubtedly, there are better ways of creating a hydrophobic seal at the guide tube-brain interface that is penetrable by fine microelectrodes. Of course, it is generally prudent to position the tips of the guide tubes as far as possible from the tissue under investigation (e.g., on the surface of the dura when this is possible).

Chronically implanted fixed microwires can remain within the cortex and, in some cases, record from the same neurons for periods in excess of one year (e.g., Porada et. al., 2000; Swadlow, 1981; 1985). For many experimental aims, however, microwires do not yield optimal

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\(^8\) Due to geometric constraints, concentric arrays of 7 or 19 channels (with one ring or two rings of guide tubes, respectively, around the center tube) are most easily fabricated when all guide tubes are of the same outer diameter.
recordings. The present work presents a system that enables the use and control of fine-diameter, precisely configured and mobile Reitboeck microelectrodes (1983a) within the brain for periods of many months and even years. It is important to know if the system described here could be useful in recording from larger brains, which may not be as stable, relative to fixed skull coordinates, as the rabbit brains studied here. Preliminary experiments in a primate (Chen et al., 2004), in which a 3-channel version of the above system was used successfully for a 3-month period, suggest the affirmative.

FIGURE CAPTIONS

1. A: A photograph of a completed 7-channel system with a single microelectrode in place within one of the guide tubes (a, on the left). The seven guide tubes are bound concentrically within thin-walled polyimide tubing (b), and are made of 33 gage stainless steel tubes (I.D. = 100 microns), the walls of which have been thinned to ~25 microns (O. D., ~150 microns, special order, Small Parts Co, Miami, Fla). The upper portion of the guide tubes are separated and positioned within a plastic template (c) that also accommodates the microdrives (d). The holes for the guide tubes are separated by ~ 1.3 mm, and the holes for the microdrives are separated from their associated guide tube holes by ~ 1 mm. The upper ends of the guide tubes are beveled (facing outward, top of guide tube on the right are indicated by the horizontal dashed arrow) for easy insertion of microelectrodes. B: Fluids are prevented from entering the guide tubes by filling them with an antibiotic ointment and creating a seal of bone wax over the tips of the guide tubes. One way to achieve this, shown here, is to secure an additional length of polyimide tubing over the guide tubes to create a space at the tips (~0.25 mm). After filling guide tubes with
antibiotic ointment, this space at the tip of the guide tube is filled with melted bone wax. The electrodes readily penetrate the wax, which forms a hydrophobic seal.

2. Microelectrode construction and the "buckling problem". A – E: Successive stages in fabricating the microelectrode and the means for preventing buckling. Dimensions given are for use with guide tubes 22 mm in length. A: Pulled and sharpened electrodes are cut to a length of 31 mm and the quartz at the rear end of the electrode is broken such that a few hundred microns of metal core extends from the upper end (arrow). B: Electrical contact with the fine platinum-tungsten core is achieved by soldering a three mm length of platinum rod (yellow, 200 – 250 micron diameter) to the core so that about 1 mm of platinum rod overlaps with the quartz insulation. The mechanical junction between the quartz and the platinum rod is reinforced with cyanoacrilate cement. C: The electrode is threaded through a 7 mm length of polyimide tubing (red, 250 microns I.D., 300 microns O.D., A-M systems). The I.D. of this tubing must be somewhat greater than the O.D. of the stainless-steel guide tubes (gray) that are used. This tubing is gently fitted around the platinum rod to reach a few hundred microns beyond the solder juncture of the platinum rod and the electrode core. The polyimide tubing serves two functions: (1) it further strengthens the mechanical junction between the electrode and the platinum rod and (2) it prevents buckling of the electrode as it is lowered (below). D. The electrode can now be threaded into one of the guide tubes. Once the polyimide tubing passes over the top of the guide tube, the upper portion of the electrode shaft is no longer subject to buckling as it is lowered (E).

3. Individual components and an assembled microdrive. The screw (A) with a cross-bar soldered to the top (B, for easy turning) is housed within a grooved cylinder (C) that has a
matching nut (D) soldered to the top. The screw is threaded through the nut, and its distal tip pushes down on a piston (E) which has an armature extending from its lower end (F) that exits the cylinder at ~ a 90 degree angle via a groove along the length of the cylinder. This groove serves to constrain the motion of the armature to a single axis (the z-axis). The armature will later be secured to the polymide tubing around the upper portion of the microelectrode (using melted dental impression compound) and will control its motion. The upper end of the piston is ground to a symmetrical point, which serves as a bearing that is held against the base of the screw (which is ground flat) by a small compression spring (G) that puts upward pressure on the armature. A small length of stainless steel tubing (H) fits over the bottom of the cylinder to provide a base for the compression spring. The assembled microdrive is shown in I. A complete 7-channel system is illustrated in J, with two electrodes in place in the two channels to the right. One of these electrodes (on far right) is shown secured to the piston armature with the melted dental impression compound.

4. Light (A1-C1) and electron (A2 – C2) micrographs of three of seven electrodes that had been within or above the LGNd of one rabbit for a little more than 6 months. D1 – D4 shows spikes, associated clusters, and visual receptive fields obtained during a final penetration using electrode “C” just prior to removing it from the brain. The calibration bars in the light and electron micrographs = 10 microns. Electrode "C" may have been bent as it was removed from the guide tube. The calibration bars in D = 5 degrees.

5. Light (A1 – B1) and electron (A2 – B2) micrographs showing two electrodes that been within or above the ventrobasal thalamus for a period of > four years. C1 – C4 shows spikes and
associated clusters obtained during a final penetration using electrode “B” just prior to removing it from the brain. A and B show some evidence of dissolution of the quartz insulation after this time period. The tips of these electrodes are produced by a grinding process and the junction between quartz and metal cannot usually be discerned by a change in taper. Here, however, there is a clear change in geometry where the quartz meets the metal (lower arrows in A1 and B1). Based on the position of the quartz-metal junction in freshly made electrodes (or those in the brain for only a few months, e.g., Fig 4), we estimate that the quartz originally extended considerably closer to the electrode tips (position of the upper arrows). The dashed lines in B2 show our estimation of the borders of the original quartz insulation covering this metallic tip. Calibration bars in the light and electron micrographs = 10 microns.

6. Nissl sections from one rabbit in which the guide tube array had been in place for 4 years and 5 months. This array was implanted a little deeper than we had planned, and the tips of the guide tubes inadvertently penetrated the dorsal thalamus (6A). Many freezing (and other) artifacts are present but, aside from the mechanical damage done by the guide tubes, tissue damage around the tips of the guide tubes (which had been filled with bone wax) seems minimal. B: A section taken through VB thalamus (dashed outline), where recordings were obtained. This section is ~ 1.8 mm posterior of that shown in A (because the plane of section is misaligned with that of the guide tubes). No unambiguous signs of the electrode tracks or tissue damage could be followed to this nucleus. However, it is possible that some damage above VB thalamus may be related to the microelectrode penetrations (arrow). The calibration bars in A and B = 1 mm.
7. Top: multi-unit receptive fields generated in superficial superior colliculus by five microelectrodes one week after this electrode array was implanted. These electrodes were of low impedance (< 1 Mohm), designed to be optimal for multiunit and field potential recordings, as well as for microstimulation. Bottom: receptive fields recorded from these same electrodes 12 months later. Recordings were obtained several times during the intervening months and electrodes were periodically moved to various positions within and above the colliculus. At the end of the one-year period, all of the electrodes were still mobile and, when re-positioned in superficial collicular layers, yielded receptive fields with relative spatial positions that were very similar to those initially recorded.

ACKNOWLEDGEMENTS

Supported by grants from NIMH (MH-64024), NSF (IBN-0077694), and NEI (EY13788).

REFERENCES


Figure 1
Figure 2
Figure 5
Figure 6
Receptive fields, initial recordings

Receptive fields one year later

Figure 7