Parylene as a Chronically Stable, Reproducible Microelectrode Insulator

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Abstract—One of the major problems in the design of neurophysiologic extracellular microelectrodes is the application and selective removal of the insulation. In addition to the usual problems of achieving pin-hole-free coatings and reproducible tip exposures and impedances, chronic electrode designs have the additional requirement of maintaining megohm levels of electrical isolation for months *in vivo*. A method of insulating finely tapered microelectrodes with complicated shapes by vapor condensation of Parylene-C is presented, along with a method for exposing controlled, reproducible lengths of their tips. *In vivo* and *in vitro* impedance tests and unit records obtained over 100 days in monkey motor cortex are presented. The electric arc process used to expose Parylene-covered iridium and tungsten microelectrodes is found to give cleaner recording surfaces with impedances lower than those obtainable with previously described methods. Chronic iridium microelectrodes so fabricated have recorded unit potentials and maintained constant impedances for over 4 months *in vivo*.

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An extracellular microelectrode for recording single-unit action potentials from nervous tissue is basically a high-impedance probe recording a small and highly localized potential in a volume conductor. The localized nature of the potential gradient [1] and the fragility of its source dictate a probe tip with small dimensions (typically less than 5 by 25 μm) which in turn produces a high metal/electrolyte interface impedance (typically 1-10 MΩ at 1 kHz) whose thermal (Johnson) noise may be of the same order as the recordable potential (typically 50-500 μV). Since the overall probe must have a slender profile to minimize disruption of tissue, the electrical requirement of minimal shunt losses along the insulated shank of the probe falls on a very thin dielectric coating which must be cleanly excluded from the tiny exposed tip. Reproducibility and reliability have been goals of most new microelectrode designs. Now that a variety of elegant techniques are available for finely controlled, reproducible electroetching of metal wires [2]-[6], the limiting factor appears to be the insulation.

A variety of coatings have been devised for microelectrodes designed for acute experiments, including lacquers [7], [8], varnishes [3], [9]-[12], enamel [13], [14], vinyl [15], [17], paint [18], epoxy [5], [19], glass [2], [4], [20]-[26], and silicon dioxide [27]. In each case, fairly involved and difficult to reproduce techniques are required to establish pin-hole-free uniform-thickness coatings on tapering, pointed wires with small, decreasing radii of curvature. Techniques for exposing

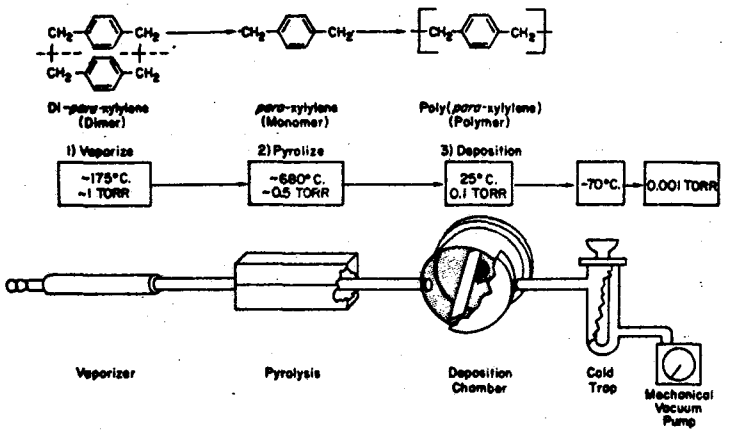

Fig. 1. Schematic of Parylene deposition process and equipment, provided courtesy of the Union Carbide Corp., New York, NY.

the tip are various, but particularly difficult to accurately reproduce. They include abrasion [28], breaking [2], laser burning [15], electric fields [12], [16], electrolysis [4], [5], [17], [19], [22], [26], curing shrinkage [3], [7], [8], [10], [11], cut ends [13], [29], shearing [9], etching [27], [30], melting [30], and simply not covering the tip during application [18].

There has been no dearth of satisfactory, if somewhat tediously fabricated extracellular microelectrodes for acute use. However, the advent of chronic microelectrodes designed to record single units without disturbance over several months [30] raised the suspicion that none of the previously employed materials was sufficiently nonreactive and electrically stable *in vivo*. Lacquers and varnishes are organic materials with limited resistance to saline. Epoxy absorbs water and eventually breaks down, although Araldite-insulated microelectrodes have been reported to have one-third of their number still intact after a month [19]. The low-melt-temperature solder glasses slowly dissolve in saline, although tolerable but falling impedances can last a month or so *in vivo* [30]. The two dielectrics used in other chronic biomedical devices, silicone rubber and Teflon, are both difficult to apply in thin uniform coats to tapering electrodes and difficult to selectively exclude from the tips: they have not been successfully used on microelectrodes, although Teflon has passed chronic tests on macroelectrodes [31], [32]. In addition, the critical design parameters of the floating cortical chronic microelectrode employed by us called for a dielectric coating on a complex shape incorporating a microweld between the short stiff electrode shaft and a delicate, ultraflexible lead wire [33].

The members of the Parylene family of long-chain polymers are deposited and polymerized by a unique method of vapor condensation which endows them with many highly desirable properties for chronic use. The fact that the resultant coating is a highly uniform thickness, conformal but nonadhesive layer of homogeneous, pure, poorly ionizable polymer led to a standardizable method of cleanly exposing precise tip surface areas with an electric field. Although Parylene is a relatively new and not widely available material, evidence of both its biocompatibility and dielectric stability in saline has accumulated. Parylene film surfaces have been implanted subdurally as test patches [34], as insulation on radiation detectors [35], and as flexible microcircuit substrates (G. E. Loeb, unpublished) without toxicity, and have been used as tissue culture substrates for neurons (G. E. Loeb, unpublished) and for fibroblasts as a potential vascular prosthesis surface [36]-[39]. Thin coatings (0.6 mil) provide better than 20-MΩ isolation of a Bathythermograph thermister probe for lowering to 6000-ft depths in the ocean [40].

In the present studies, Parylene was evaluated as an insulator for chronic floating microelectrodes with etched iridium shafts and for more conventional etched tungsten acute extracellular microelectrodes. With both types, tip exposure was found to be reliably and reproducibly controlled by easily varied parameters of the electric arc used for exposure. Tip impedances were lower and more stable by this method than by the previously described tip exposure method of locally melting the Parylene [33].

Parylene is the trademark of a family of linear polymers made from a variety of substituted structures of di-para-xylylene. Parylene-C, which has the best tradeoff of properties for biomedical applications and is the most generally available, has a single chloride atom on each benzene ring. As shown in Fig. 1, the raw material consists of a dimer in which two para-xylylene moieties are joined at both ends, creating a secondary ring structure. The powdered dimer is vaporized by radiant heat absorption in an evacuated chamber and passes through a pyrolysis zone where the higher temperature cleaves the dimer into two divalent radical monomers. The monomer molecules enter the evacuated deposition chamber where devices to be coated are at room temperature. The molecules condense on the surfaces and spontaneously link free radical terminals into long, randomly oriented polymer chains. Because of the large average number of collisions required per polymerization (10 000) and the short mean free path of the molecular vapor (less than 1 mm), the coating forms slowly and uniformly over surfaces with both sharp edges and deep crevices, with no pin holes found even in submicron film thicknesses [41]-[44]. Since the radicals react chemically only with each other, the resultant film is only mechanically bonded to

TABLE I
COMPARISON OF PARYLENE-C WITH OTHER BIOMEDICAL POLYMERS

	Parylene-C	Teflon-FEP	Teflon-TFE	Silicones	Epoxies	Urethanes
Tensile strength, lb/in^2	13 000	3000	3400	800-1000	4-13 000	175-10 000
Elongation to break, percent	200	300	300	100	3-6	100-1000
Water absorption, 24 h percent	0.01	0	0	0.12	0.08-0.15	0.02-1.5
Water vapor transmission g/mil/100 in^2, 24 h, 37°C, 90 percent RH	0.5	–	3	4.4-7.9	1.8-2.4	2.4-8.7
T melt or distortion, °C.	280	290	330	to 300	to 220	170
Vol. resist., 23°C, Ω · cm	9×10^{16}	10^{17}	3×10^{16}	2×10^{15}	10^{12}-10^{17}	to 10^{15}
Dielectric Constant, 1 kHz	3.1	2.1	2.08	3.4-3.8	3.5-4.5	4-7.5

Note: Data obtained from New Linear Polymers by H. Lee *et al.* [46] and Parylene brochure published by the Union Carbide Corp., NY [44].

the substrate, with no chemical adhesion unless special surface treatments are used. Spontaneous polymerization eliminates potentially toxic impurities such as catalysts and plasticizers and inhomogeneities in film structure. Coating thickness is essentially linearly proportional to the weight of dimer with which the system is charged and exerts no distorting forces on the substrate at any thickness (2-3 mil maximum per cycle). Pertinent physical characteristics are listed in Table I in comparison with a variety of other biomedical plastics.

Specific information for the construction and operation of a Parylene deposition chamber is available under a variety of licensure arrangements with Union Carbide Corporation, New York. Custom deposition facilities are available at Union Carbide and many of their licensees.

MATERIALS AND METHODS

Iridium shaft chronic floating microelectrodes were prepared by the previously described methods of cyanide electroetching and microwelding to gold lead wires [33]. Tungsten microelectrodes were prepared by crimping 5-mil tungsten wires in stainless steel hypodermic tubing and electroetching with 60 Hz alternating current while being dipped automatically in and out of a solution of 71 gm $NaNO_2$ and 34 gm KOH in 100 ml distilled water [24]. This results in a fairly uniform taper from a 1-2 μm tip diameter to 5-6 μm at 50 μm up the shaft.

All electrodes were coated with a uniform layer of 3-3.5 μm of Parylene-C in a standard 9-in deposition chamber [44] as illustrated in Fig. 1. In those electrodes designated as "heat-exposed" tips, the insulation was removed from the tip by quickly bringing a hot platinum filament in a microforge [45] to within a few microns of the tip, resulting in an apparent burning away of the Parylene on the distal 10-15 μm of the pointed shaft. Iridium microelectrodes designated as "arc exposed" were positioned a controlled distance of 0.08-1.0 mm from a platinum ground plate by visualizing the electrode tip and its reflection in the plate under a low power microscope objective. The 60-Hz ac voltage was applied manually by gradually increasing the primary voltage of a high-voltage transformer whose output was current limited by 50 MΩ in series with the electrode. When the insulation broke through (usually at 1000-1500 V ac), there was an audible snap and a visible corona around the tip. The voltage was turned off manually, either quickly or, in some cases, after allowing the corona to persist a few seconds.

This method proved unsatisfactory for tungsten as the alternating current burned off the point before the voltage could be shut off, so an automated arcing system was constructed. A dc potential was applied with the electrode kept negative with respect to the ground plane, rising with a 5-s time constant to a maximum potential of 3600 V dc. When the insulation broke through, the current pulse was detected electronically and a variable timer started, allowing a duration of 0.5-3000 ms to be set for the corona which was terminated automatically. A current-limiting 27 MΩ resistor was placed in series with the electrode and the gap was varied from 0.02 to 0.5 mm.

Following insulation removal, all electrodes were tested immediately with a standard procedure. Each was lowered into a glass cuvette filled with saline in which the tip and length of shank beneath the surface could be observed with a transilluminated 60X microscope. Approximately 1 μA rectified 60-Hz current was applied for a few seconds with the electrode negative with respect to a large platinum ground in the bath. Streams of electrolysis bubbles were seen to come from the exposed tip and a visual check was made for bubbling along the shank signifying insulation defects. Approximately 1-μA capacitively coupled 1-kHz ac constant current was then passed through the electrode and the amplified voltage across the electrode compared with calibrating signals to determine the magnitude and phase angle of the tip impedance (0° = pure resistance, 90° = pure capacitance). As a further check for leaks and shunting across the insulation, the impedances obtained at initial contact with the saline and after 1-cm-deep immersion were compared. Dimensions of exposed tips were obtained from scanning electron micrographs for iridium electrodes and 500X light microscopy for the larger tungsten tips.

Electrodes tested chronically *in vitro* were placed in sealed chambers containing sterile saline or plasma and incubated at 37°C. Periodic impedance tests were carried out with a 1-kHz 10-mV sine wave without dc current passage. Electrodes tested *in vivo* were sterilized in 70 percent isopropyl alcohol and implanted by hand in monkey motor cortex using the skull chamber configuration previously described [33]. Tungsten microelectrodes used acutely were arc exposed and impedance tested as noted above immediately prior to recording single-

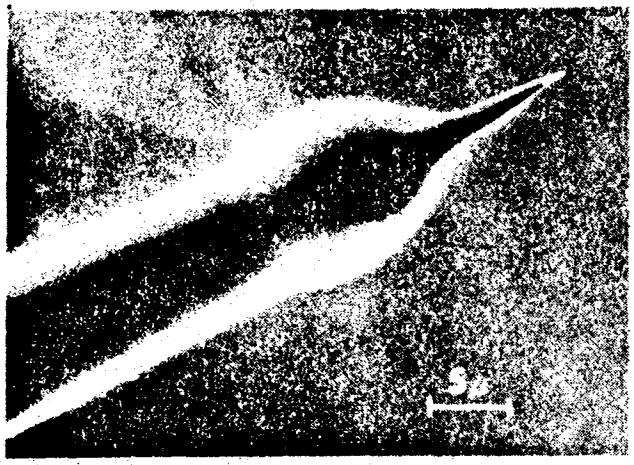

Fig. 2. SEM view of Parylene-C-insulated iridium microelectrode, tip exposed in a microforge by local heating.

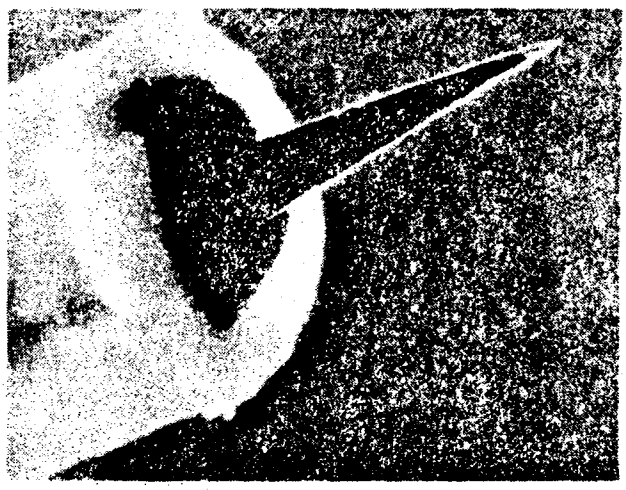

Fig. 3. SEM view of Parylene-C-insulated iridium microelectrode, tip exposed by an electric arc in an ac field. Note clean metal surface with rilled texture and sharp, symmetrical border of the light-colored Parylene sleeve.

unit potentials in cat lumbar spinal dorsal root ganglia, where they were required to survive multiple penetrations of the undissected, tough dural-perineural sheath.

Results

Tip Exposure Parameters and Impedance

Using heat to burn Parylene from the tip of a microelectrode produced the type of exposure seen in Fig. 2, where there is a length of tapering tip (approximately 10 μm long) which has had its coating considerably thinned but apparently not completely removed. An accurate measure of exposed metal surface area is impossible to obtain and the thinned portion of Parylene might be expected to have significant capacitive reactance at the test frequency of 1 kHz (and at frequencies present in neuron action potentials). This thin film and the apparently melted, swollen area proximal to it can be expected to have undergone considerable chemical degradation on the basis of the known sensitivity of Parylene-C to heat in an oxygen containing atmosphere [44].

The scanning electron micrograph (SEM) in Fig. 3 shows the typical tip exposure obtained by ac arcing an iridium tip. The 3 μm Parylene coat ends abruptly with slight fanning out of the edges rather than the rounding expected of an oxidative or thermal process. The iridium metal is cleanly exposed and the characteristic fibrillar grain structure accentuated by the etching process can be clearly seen; the point tapers to less than 0.1 μm without blunting.

Table II shows the arc parameters and SEM-determined dimensions of 10 iridium microelectrodes exposed in this manner. There is a clear trend towards longer tip exposures and hence greater surface areas as the gap for the arc increases which is reflected in generally lower impedances. The extended corona duration may also increase the length of exposure somewhat, but was not believed to be a significant factor at these currents. Poor control of metal taper is manifested by the poor correlation of base radius with exposed length, and this is probably a major contributor to the uneven results. Even with careful control of etching parameters, the long etch times required for the refractory iridium metal and inherent inhomogeneities in the crystalline structure of fine iridium wire probably made this unavoidable. The mean exposed area for the four electrodes indicated by crosses is 13.8 $\mu m^2 \pm 3.7$ μm^2 standard deviation. The mean impedance is 0.82 ± 0.26 MΩ with a mean specific junction impedance of 11.3 M$\Omega \cdot \mu m^2$. The latter is a measure of metal-electrolyte junction conductivity which we define as the product of electrode impedance and apparent tip surface area. In addition to inherent properties of the metal and solution, the contributions of "roughness" and "cleanness" to real surface area are probably the major factors in this index.

TABLE II
AC Arc Exposure Parameters and Impedance Data for Iridium Microelectrodes

Gap (mm)	Tip Length (μm)	Base Radius (μm)	Area (μm^2)	Z (megohms)	Phase Angle (°)
0.08*	1.6	1.2	8.1	1.6	62
0.15*	1.9	0.9	6.3	2.0	71
0.30	2.5	0.9	8.1	1.4	72
0.60†	2.8	1.0	9.5	0.7	72
0.60†	5.9	0.7	14.2	1.2	50
0.60*	7.4	0.8	20.0	1.5	68
0.75†	4.1	1.0	13.0	0.6	65
0.75†	3.8	1.4	18.5	0.8	71
1.0	5.3	1.2	21.5	0.5	68
1.0*	22.0	1.4	95.0	0.4	71

Note: 50-MΩ current-limiting resistor used for all electrodes. Base radius refers to base of conically shaped exposed tip.
*Corona duration 2–3 s (otherwise 0.3–0.5 s).
†Average values given in text.

DC arcing with automatic corona duration control was tested at a variety of parameters with 21 tungsten and 6 iridium electrodes. For both it was apparent that insulation removal took place in two separate steps. First, a symmetric conical cap of Parylene was blown off the tip resulting in an exposure length dependent on gap and electrode taper for even the shortest corona duration (0.5 ms). This cap was always less than 2–3 μm for any gap with tungsten electrodes, which tend to have very sharp points. The iridium exposure was similar to that with ac fields. Prolonging the corona for either metal caused gradual, symmetrical sputtering away of the insulation back

from the exposed tip, with the rate highly dependent on gap size over the range 0.02–0.5 mm. In addition, small gaps and long coronas tended to blunt the sharply etched points of both metals, but this could be reduced while still removing insulation with longer corona duration at larger gaps.

A series of 10 tungsten microelectrodes at a gap of 0.1 mm and 500-ms corona duration had a mean exposure length of 14.3 ± 2.0 μm with impedance 1.10 ± 0.25 MΩ at approximately 70° phase angle. A rough estimate of areas by light microscopy produced a mean of about 180 μm^2 for a specific surface impedance of about 200 M$\Omega \cdot \mu m^2$. Iridium specific surface impedance seemed similar to that of ac arced electrodes. For both electrode metals, it was possible to repeatedly extend the exposure of initially small tips by reestablishing the corona at any desired gap and duration, allowing one to titrate exposure length, tip impedance, and tip sharpness precisely and somewhat independently.

For all microelectrodes exposed by any of the above methods, bubble testing always showed one and only one site of metal exposure, namely at the tip. Impedances never dropped by more than 10 percent during 1-cm deep immersion of the Parylene insulated shank, and this drop was always gradual and consistent with a small, purely capacitive shunt across the thin dieletric film. Cathodal bubbling had the additional property of considerably lowering and stabilizing the initial impedance values obtainable, probably by reducing surface oxides accumulated during exposure.

Chronic in Vitro Impedance Testing

Fig. 4 shows the impedances in megohms at 1 kHz for heat-exposed iridium electrodes over 52 days in saline and plasma. Fig. 5 shows similar curves for three arc-exposed iridium electrodes in saline. After some initial fluctuation, both types appear to settle to within a factor of 2 of their original impedances. There is no evidence of leaks or increased shunting developing during this test period.

Chronic in Vivo Testing

Figs. 6 and 7 show mean impedance values for 11 heat-exposed and 12 arc-exposed iridium microelectrodes, respectively, implanted in the motor cortices of two monkeys. In both figures, the value at zero time marked *T* represents the mean of *in vitro* testing immediately following tip exposure, with the range indicated by the crosses. Weighting coefficients were assigned to each electrode to normalize its impedance to this mean value, and the subsequent points on the curve represent the mean and standard deviation of normalized impedance values. Thus the standard deviations represent the amount of random fluctuation over time (i.e., unpredictability) of the electrodes rather than initial differences. Normalization based on the first *in vivo* measurements produced no significant change in apparent stability.

The heat-exposed electrodes start at fairly high impedance values, despite apparent tip exposures of 10–25 μm by light microscopy, and proceed to go even higher in the first days. There is a consistent and abrupt fall in impedances at 20–40 days to 20 percent of the initial values. At this point, multiunit recordings are still obtainable but signals are smaller and more numerous. While previously thought to be leveling off [33], continued impedance monitoring to 275 days shows further impedance drop with concomitant loss of any useful recordings.

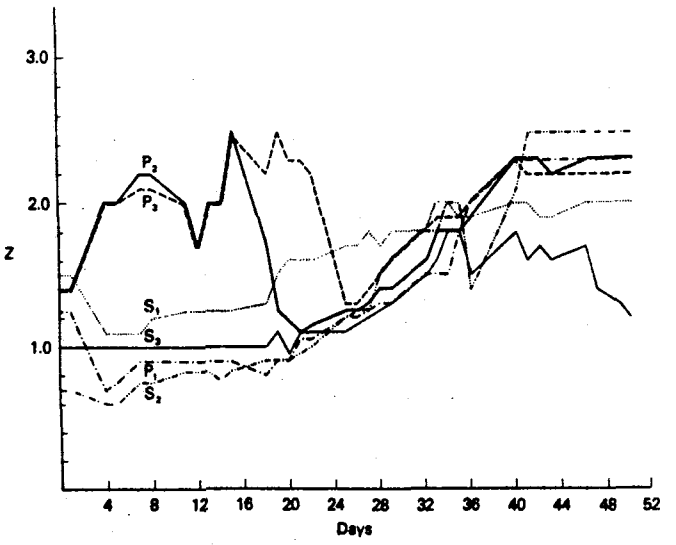

Fig. 4. Impedance in megohms at 1 kHz for 6 heat-exposed Parylene-insulated iridium microelectrodes for 52 days incubation at 37°C in physiologic saline (*S*1–*S*3) and plasma (*P*1–*P*3).

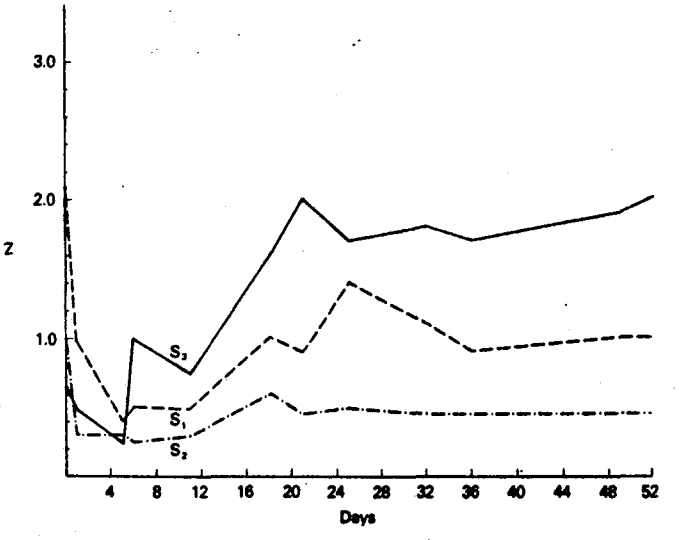

Fig. 5. Impedance in megohms at 1 kHz for 3 arc-exposed Parylene-insulated iridium microelectrodes for 52 days incubation at 37°C in physiologic saline.

Arc-exposed electrodes with smaller apparent tip exposures (4–10 μm long) start at lower impedances and drop slightly in the first few days, quickly stabilizing at values near their preimplantation levels which persist unchanged for the 100-day course (Fig. 7). Fig. 8 shows the impedance curve for one of these electrodes with inserts showing typical unit activity obtained during this period. There is a general trend from single-unit to two- and three-unit records in many electrodes over this period, but signal size is stable and adequate for spike waveform sorting (100–500 μV). In this monkey, unit records on most electrodes were lost around day 136 due to a hematoma which developed in the chamber. The animal was sacri-

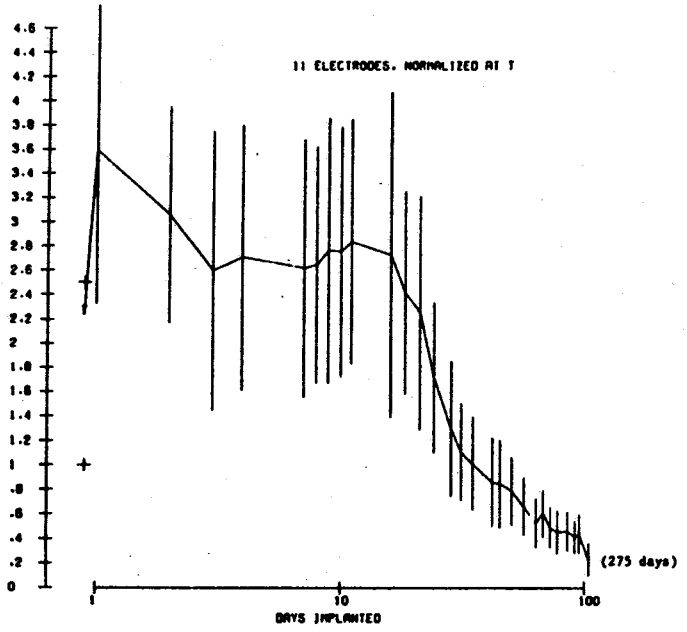

Fig. 6. Impedance in megohms at 1 kHz for 11 heat-exposed Parylene-insulated iridium microelectrodes in monkey motor cortex. Initial value at *T* represents mean of *in vitro* tests conducted before implantation, range given by plus signs. Final value (marked "275 days") indicates continuing increase of exposed metal surface area. See text for explanation of vertical lines indicating normalized standard deviation.

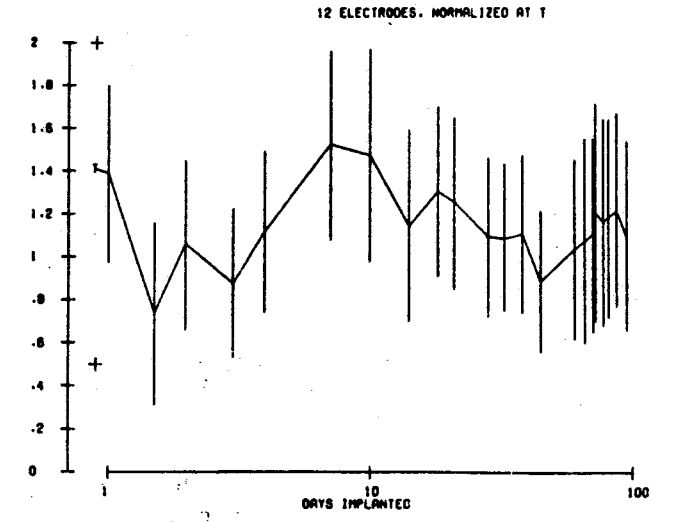

Fig. 7. Impedance in megohms at 1 kHz for 12 arc-exposed Parylene-insulated iridium microelectrodes in monkey motor cortex.

ficed on day 142, at which time electrode impedances were still essentially unchanged. The microelectrodes slipped freely from the fixed brain on gross dissection and both are being processed for further study. Fig. 9 shows an arc-exposed iridium electrode removed after 50 days in cat cerebral cortex. The metal surface remains cleanly exposed and demarcated from the apparently intact Parylene sleeve.

Acute in Vivo Testing

Arc-exposed tungsten microelectrodes (10-15 μm, 1-2 MΩ) were tested in cat dorsal root ganglia because of the notoriously dense, tough collagenous dural sheath and internal stroma which has led other investigators to resort to sharp dissection and digestive enzymes [47]. Microelectrodes survived repeated passes through the intact sheath, easily isolating 10-20 units per pass with 200-500-μV potentials at less than 30-μV peak-to-peak noise (100-5000 Hz) [48]. Occasional electrode failures were attributable to bending the metal as seen on light microscopic examination; tearing of the insulating film was never observed. The unusual tip shape, i.e., blunt insulation cuff behind a sharp protruding tip, was not detrimental to obtaining a high yield of well-isolated units per pass. Parylene-insulated tungsten microelectrodes found and held considerably more units than glass-insulated platinum-iridium microelectrodes [22] in the same preparation. The smooth, even, hydrophobic shank appeared to penetrate with less resistance and, presumably, less compression. The square edges shown in Fig. 3 (before use) are probably somewhat rounded by the trauma of penetrating meninges (see Fig. 9).

Discussion

Arc-exposed microelectrodes achieve significantly lower specific surface impedances which are much more stable *in vivo* than those of microelectrodes with heat-exposed Parylene [33] or other dielectrics reported to date. This seems largely attributable to the arc-exposure technique and certain inherent physical and electrical properties of vapor-deposited Parylene-C which make it possible. While microelectrodes of this design are highly reliable and effective for obtaining single neuronal units in acute penetrations, the main advantage of the technology appears to be the ability to reliably protect complex, delicate assemblies over long periods *in vivo*.

The arc-exposure process appears to take place in two stages. First a symmetric conical cap of Parylene is blown off the tip, probably as a result of electrostatic force exceeding the tensile strength near the tip. The extremely uniform coating thickness keeps the exposure symmetrical but the length is quite dependent on control of terminal taper. For this reason, insulation removal by sputtering in a dc cathodal corona is more reliable with the additional advantage of allowing repeated small removals controlled by hand while observing under the microscope. This method does produce some blunting for both tungsten and iridium, reducing the needle sharp tips remaining after stage one from under 0.1 μm (see Fig. 3) to perhaps 1-2 μm. However, there appears to be a feeling among some investigators that overly sharp tips puncture neurons more frequently and may be undesirable. This degree of blunting is still compatible with piercing dense connective tissue.

It should be noted that the tip sizes being used for arc-exposed tungsten and especially iridium are extremely small whereas the observed tip impedances are quite reasonable for extracellular work (0.5-2 MΩ at 1 kHz). It has frequently been the practice of investigators desiring to work with tips this size to apply platinum black coatings on platinum-iridium [49]-[51] or on tungsten primed with electroplated gold [47] to achieve tolerable impedances. The fragility and instability of platinum black, as well as the extra construction steps, make its elimination desirable and probably helps contribute to the stability seen here both *in vitro* and *in vivo*. The most likely explanation for the low specific surface impedances of arc-exposed elec-

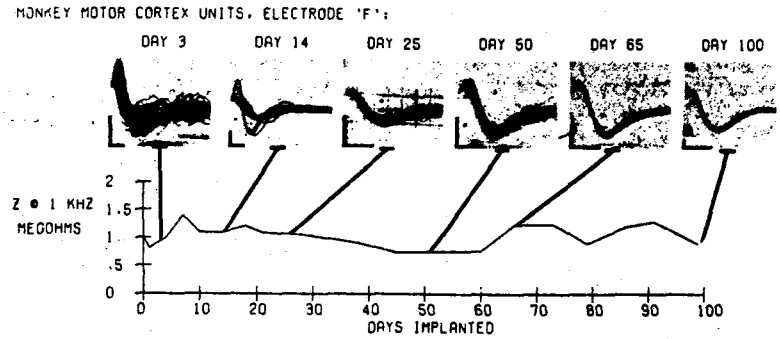

Fig. 8. Detail of impedances measured for one of the electrodes in Fig. 7 (arc-exposed Parylene) with inserts showing typical single unit records from presumed pyramidal cells obtained from this electrode during the 100-day period. Horizontal bar in each tracing represents 0.2 ms; vertical scale indicates 100 μV.

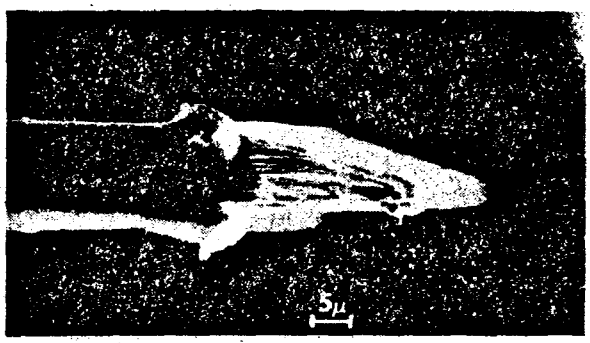

Fig. 9. SEM view of arc-exposed Parylene-C-insulated iridium microelectrode removed after 50 days in cat cerebral cortex.

trodes is the extremely clean metal surface so obtained, since heat-exposed tips have the higher impedances seen in many other microelectrode designs. This would be consistent with the large phase angles observed, indicating predominantly capacitive double-layer reactance with minimal access resistance. The rough, rilled surface of etched iridium probably provides a real surface area for capacitive conduction much larger than that observed visually, an area that may be partially covered by oxidized, melted, or fragmented debris left by adherent dielectrics and/or other exposure methods (compare Figs. 2 and 3).

The comparison of *in vivo* and *in vitro* chronic impedance records also indicates differences in tip surface accessibility. Arc- and heat-exposed electrodes behave similarly *in vitro*, with small random fluctuations initially settling to stable values (see Fig. 4 and 5). *In vivo*, however, heat-exposed electrodes immediately increase their impedance on implantation whereas arc-exposed electrodes have constant or somewhat lower impedances (see Fig. 6 and 7). We hypothesize that the degraded Parylene residue on heat-exposed tips attracts macrophages and retains cellular debri acquired during insertion, increasing the access resistance initially. This process, particularly severe on platinum black surfaces, has been called "poisoning" by others [49]. The cellular response also appears to be the cause of the large, steady, long-term impedance drop seen in heat-exposed but not arc-exposed microelectrodes. While the degraded Parylene on and just proximal to the tip seems stable *in vitro*, cracks and loss of tensile strength probably allow macrophages to eventually break it apart *in vivo*. The arc-exposed electrodes show no sign of this by either electrical data or postmortem SEM examination (see Fig. 9). (Parylene layers that have lowered tensile strength and elasticity because of faulty deposition technique have also been seen to survive *in vitro* chronic tests but fail with gaping cracks after several weeks *in vivo*).

The complete lack of pin-hole failures on initial testing or when acutely stressed in dorsal root ganglion experiments as well as the symmetrical removal when subjected to high voltages all tend to confirm claims regarding the homogeneous, conformal nature of the vapor deposition process. The long-term presence of electrically active neurons within microns of the plastic surface is further indication of the biocompatibility of this material. An additional feature of Parylene used incidentally in some of these tests is its tendency to discourage proliferation of fibroblasts because of its hydrophobic surface [38]. Plexiglas windows in the skull chambers when coated with Parylene-C remained clear for many months despite vigorous regrowth of surgically interrupted meninges on the cortical surface, thus permitting good visualization of the electrodes and leads riding on the brain's surface.

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