Experimental Brain Prosthesis for Stroke

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Abstract:
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Electrical control of motor behavior by programmed electrical stimulation of the brain has been described. Such programmed brain stimulation is referred to as a "brain prosthesis," meaning, in effect, "artificial brain."

Areas in the brain related to the production of elementary movements were located. From these preliminary experiments it was evident that programmed stimulation of the brain at sites typically unaffected by stroke could produce a "purposive" sequence of motor behaviors.

Monkeys were made monoplegic by surgical (two-stage) resection of appropriate cortical and subcortical regions. After recovery electrodes were implanted in the brain. This technique is described.

The electrodes are linked to a multiple-electrode programmable brain stimulator. The stimulator and computer programming make it possible to specify which electro-stimulators are to be turned on, and strength and duration of current to produce a pattern of complex motor function.

Programs of stimulation, which cause the paralyzed limb to reach out, grasp an object (such as food), and bring the object rapidly and smoothly to the mouth, have been written. The ultimate question of applicability of this model in humans remains to be studied.

ADDITIONAL KEY WORDS artificial brain brain stem monoplegic hemiplegic electrical stimulation

In 1966, a method for the electrical control of behavior by programmed stimulation of the brain was described.¹ At the end of that report it was suggested that the method might be employed to stimulate the brain to restore nervous system function lost by injury or disease; that is, the programmed brain stimulation could serve as a "brain prosthesis." In this article we describe such a brain prosthesis as it might be applied to recovery from paralysis due to stroke.

By "brain prosthesis" we mean, in effect, "artificial brain," a term used for the brain just as "artificial heart," or "artificial lung," or "artificial kidney" are used to denote devices and techniques for replacing functions of those organs lost by injury or disease. This is in contradistinction to replacing a peripheral function controlled by the brain, such as movement of an arm, by devising an artificial arm when the brain has been injured. Our approach, instead, is to replace the lost peripheral function due to brain injury by altering the function of the brain itself. Thus, our method is not unlike that employed by Brindley and Lewin² for a visual prosthesis. "Experimental" in our title refers to the fact that our studies have been limited to animals, primarily monkeys, and no attempt has been made to extend our work to the clinic. Of course, we do hope and expect that with improvements in technique and instrumentation our results will be applicable to humans.

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Programmed Stimulation of the Brain

The basis of our method is programmed electrical stimulation of the brain, details of which have been published elsewhere, whereby brain tissue not damaged, but somehow involved in the lost function, is stimulated to function in time as it might normally. In order to use the principle of programmed stimulation for simulated stroke, we had to determine just where in the brain, other than the cerebral cortex affected by the stroke, we could stimulate to produce purposeful movements. Many studies had shown that electrical stimulation of subcortical structures of the brain can produce skeletal motor activity, such as movements of the head, foreleg, hindquarters and muscles of the face. Even higher levels of behavior can be elicited by stimulation of brain stem nuclei, including “normal” progressions in time and space such as attack, withdrawal, sitting, standing, preening, seeking and eating of food, and the like. These findings suggested to us that electrodes could be placed in various areas of the brain and each locus electrically stimulated to produce some elementary movement much as the brain produces the movement normally. Then, if many electrodes could be stimulated simultaneously and sequentially according to some pattern or program related to normal behavior, we should be able to produce coordinated limb movements and thus any “goal-directed behavior” eliminated by a stroke.

Our procedure for locating areas in the brain for producing the elementary movements was in three steps:

1. Motion pictures were made of simple motor acts of monkeys living in a compound. Such behaviors as eating, grooming, locomotion, play, aggressive behavior, responses to novel stimuli and the like were analyzed to determine into which elementary movements entered as a function of time.

2. Extensive brain-mapping studies were conducted to determine where in the brain one must stimulate to produce the various elementary movements recorded on film in step (1). Using stereotaxic procedures on several species of monkey and apes, but primarily the Rhesus monkey (Macaca mulatta), electrodes were placed into the nuclei of the cerebellum and the vestibular nuclei of the brain stem, as well as the reticular formation and many other brain stem structures. Over 200 locations were found in which elementary movements could be produced by electrical stimulation. These elementary movements included flexion and extension of all four limbs at the wrist, elbow, shoulder, ankle, knee, or hip; clenching and spreading of the fingers and fine digital movements; opening and closing of the mouth; movements of the tongue in and out; curling or sideways movement of the tail; movements of the eyes, singly and together, and dilatation of the pupils; and many autonomic responses such as modification of heart or respiration rate. In addition, it was found that the movements were much more precise than can be elicited by stimulation of the motor cortex.

In all cases it was found that the extent and complexity of movement was directly related to current strength. The optimum electrical parameters for motor production were 200 to 300 rectangular, monophasic, negative pulses per second, 0.1 to 1.0 msec pulse duration, with base-to-peak currents varying from 50 to 200 μA for a complete limb movement. A stereotaxic atlas and brain-stimulation manual describing these results, which can be used by others for brain prosthesis in the monkey, is being published separately.

3. The final step was to try to combine the first two steps to produce, or directly control, the behaviors seen in an awake animal. Up to as many as 60 electrodes were chronically implanted in each of several monkeys under aseptic surgery. When an animal had fully recovered from the implant procedure (usually two weeks to a month), programmed stimulation of the brain was then carried out in the awake animal. This was done on a moderate scale by using separate biological stimulators, such as the Grass Model S-4, for each of up to six electrodes, and to program the operation of the stimulators by electronic “gates” produced by waveform generators such as the Tektronix 160 series. Of course, with such a relatively few electrodes under programmed control only the simplest of behaviors could be reproduced.
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From these preliminary experiments it was evident that programmed stimulation of the brain at sites typically unaffected by stroke could indeed produce a "purposive" sequence of motor behaviors, and we could therefore proceed with an experimental prosthesis for stroke. Selected monkeys were made monoplegic or hemiplegic by removing cortical and subcortical regions in one hemisphere of the brain involved with controlling limb movements on the opposite side of the body. It is recognized that this procedure is not an exact equivalent to stroke, since stroke is due to lack of blood in the affected cortical and subcortical region by a cerebral vascular accident of one sort or another. On the other hand, selective cortical ablation is much more precise in producing paralysis than is occlusion of portions of the anterior or middle cerebral arteries, especially when only one limb or parts of a limb are to be paralyzed.

The general procedure we use is as follows. Adult monkeys are preferred to younger animals because skull growth is complete, an important consideration when electrodes and connectors are cemented to the skull for long periods of time. Using strict asepsis a monkey is anesthetized and placed in a stereotaxic instrument. A bone flap is made over the region of the central sulcus and the meninges are retracted. Electrical stimulation of the exposed cortical surface (monophasic, monopolar pulses of 1.0 msec duration, 250 pps and in some cases 60-cycle sine wave) is then used to map the exposed area for limb movements. Locations that produce limb movements with stimulation are labeled and are then excised electrosurgically and by suction. The lesioned area is packed with Gelfoam to prevent hemorrhage, the meninges and bone are repositioned, and the skin is sutured.

In these case of the monkey Bruno, whose brain is illustrated in figure 1, electrical stimulation on both sides of the central fissure and near the top of the brain (the upper bone edge is the midline in this monkey) produced movements in the right arm, the limb to be paralyzed in this case. Labeled numbers were placed on the cortex, as shown in (A), delimiting the portions sensitive to stimulation, and the portion of the brain under the numbers was removed (the inner dotted line in [B]). This particular result was surprising, since the area of the brain we excised was usually the portion involved in controlling the hindlimbs, while the forelimb was controlled by an area more lateral. Nevertheless, when this monkey was sufficiently recovered from surgery, it was indeed the right arm that was paralyzed to voluntary movement, though there also was evident weakness in the right hindlimb.

FIGURE 1

(A) A still enlargement of the exposed cerebral cortex of an adult male Rhesus monkey named Bruno; from a 16-mm film of the surgery producing paralysis in Bruno's right arm much as an actual stroke might do. Numbers are bits of paper placed on the cortex to identify the margins of cortex which, upon direct electrical stimulation, are identified with right arm or hand movement. (B) A drawing of a side view of the Rhesus monkey brain; the upside down portion represents the medial surface of the hemisphere. The circled "T" identifies the central fissure, which in (A) is the blood vessel running between numbers 2 and 3 and beyond. The inner dotted line of (B) delineates the margin of cortex identified by the numbers in (A). All cortex within this region was removed first as described in the text. After two months, additional cortex was removed as shown by the dashed lines.
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Following surgery, monkeys were observed for at least one month in order to determine the nature and extent of their paralyses. During this time they were observed alone in a standard primate cage and later in a larger 12' x 10' x 12' compound. Tests were administered to determine their ability to pick up and manipulate small objects and otherwise use the disabled limb. We have found that recovery in the paralyzed limbs is much more rapid after the animals were put into the larger compound and had the opportunity to move around and use their limbs. Often within a few hours after being moved into these larger living quarters a monkey will display an appreciable amount of function in a limb that was never observed to be used while the monkey was housed in a smaller cage.

The animals that showed a substantial degree of recovery in their paralyzed limb(s) were operated on a second time during which additional cortical tissue was removed. For example, in Bruno much of the function of the right arm had returned after two months. Electrical stimulation of the exposed cortex during the second operation revealed that the tissue adjacent to that which had been removed earlier was now sensitive to stimulation, whereas in the first operation it was not. Such a finding also has been reported by others. This portion of cortex was removed electrosurgically and by suction (the outer dashed line of fig. 1B), and the bone flap restored. After this operation paralysis in the right arm was quite severe with little or no recovery over an extended period of time, suggesting that the adjacent cortex had "taken over" the right arm function.

At this stage a monkey is ready to have electrodes implanted in the brain for eliciting movements in the paralyzed limbs with electrical stimulation. To accomplish this we used a technique for inserting electrodes into the brain of awake animals restrained in a chair. This technique involves permanently attaching an electrode guidance platform to the paralyzed monkey's skull while the monkey is anesthetized and in a stereotaxic instrument. The platform is made of dental acrylic and contains an array of holes through which electrodes can be inserted into the brain with stereotaxic accuracy (fig. 2). It is aligned above the monkey's head with the stereotaxic apparatus and is attached to the skull with screws and acrylic dental plastic. The skin below the platform is removed so that electrodes can be inserted directly through the skull without piercing the skin first.

FIGURE 2

Monkey Mildred, awake but tranquilized, with an electrode guidance platform and Amphenol plug attachment for implanting electrodes into the brain. (A) The guidance platform contains an array of holes for inserting electrodes with stereotaxic accuracy; cemented-over holes contain electrodes already implanted. (B) Connector screwed to baseplate for stimulation and testing of electrodes.
The electrodes we use are made of 28-gauge hypodermic tubing which contain a 0.25-mm diameter stainless-steel wire. The wire is insulated with a nontoxic epoxy resin except for 0.5 mm that protrudes from one end of the tubing. This tip is used as the cathode for stimulation and a stainless steel screw in the skull serves as the reference electrode. On those occasions when a multiple chain of electrodes must be used vertically in the same stereotaxic plane (that is, in the same skull hole), a commercially available stainless steel array is used. These are constructed of number 316 wire, 0.075 mm in diameter, with quad Teflon-coated leads composed of six contacts of 1-mm exposed wire each and separated by 2 mm.

One electrode or chain of electrodes is implanted in a subject in a given session. The monkey is tranquilized with Innovar-Vet (McNeil Laboratories) and positioned in a standard primate chair (fig. 2). After application of a local anesthetic, a small hole is drilled through the skull using a hole in the platform as a guide. The hole in the skull is made on the side contralateral to the cortical lesion, i.e., on the same side as the paralyzed limb, because most limb movements evoked by stimulation in the brain stem occur on the same side as stimulation. An electrode is lowered into the brain in 1.0-mm steps through the hole in the skull. Motor responses to stimulation are initially tested at each step as the electrode is lowered.

After each location is found that produces a distinct elementary motor response, electrodes are permanently fixed by bending the electrode on top of the platform and attaching it to the platform with acrylic (fig. 2A). The electrode is then connected to an Amphenol plug that is housed in a box made of acrylic. The box is attached to the guidance platform with screws (fig. 2B), and is removed from the platform only when electrodes are inserted into the brain. In Bruno, 13 locations were found that upon stimulation produced movement in his paralyzed right arm. Movements in this limb included rotation of the wrist, arm turning in toward the body from the shoulder, arm up from shoulder, arm up from elbow, arm back from shoulder, arm straight out from the body, rotation of forearm out from the body at the elbow, flexion of the thumb, and several other elementary movements. Exact location of each electrode can only be determined by histological examination, so we are not too certain of the structures in which the electrodes reside. This is because more than one location can cause the same movement, and because there is no suitable stereotaxic atlas for an adult Rhesus monkey (for Bruno, our placements ranged from A1, L3, H-2, arm up from elbow, to P13, L3, H-5, arm up from shoulder).

**Multiple-Electrode Programmable Brain Stimulator**

The stimulating and programming equipment referred to above for our preliminary work was

![Figure 3](http://stroke.ahajournals.org/)

The complete brain prosthetic system for programmed stimulation of up to ten electrodes. Monkey Louie in the foreground illustrates how the right arm can be made to extend up and out from the body, while the right hand is made to be open. In the left background is the Linc-8 computer, while in the right background is the Programmed Brain Stimulator. A teletype, used for calling forth a particular program of movements, is not shown.

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too limited to successfully control the full operation of a paralyzed limb, let alone the two or more limbs that might be affected in an actual stroke. We therefore designed and constructed a system for multiple-electrode brain stimulation that could be programmed and operated by a laboratory-sized computer, in our case a Linc-8 (manufactured by the Digital Equipment Corporation, Maynard, Mass.). Only ten channels of stimulation were developed at first, with the possibility for future expansion to any number of electrodes.

The system consists of four parts (fig. 3): (1) A ten-channel programmable brain stimulator; (2) the Linc-8 computer with appropriate interfacing equipment; (3) the software programs controlling the system; and (4) a monkey whose movements are to be produced by programmed stimulation of the brain. The ten-channel Programmed Brain Stimulator (PBS) actually consists of ten separate stimulators, each containing its own control circuitry. The basic stimulator consists of a current generator that provides negative going pulses into any low impedance load from 0 to 1 milliamperc (mA). The remainder of each stimulator circuit consists of pulse generators, ramp generators, time generators, and solid-state multiplex switches. These devices, all constructed on a 5" x 5" standard DEC computer card of mostly integrated circuits, control the output of the current generator so that pulses of 1-msec width are delivered to the animal's implanted electrodes at the usual repetition rate of 250 pps. Current intensity, controlled by the ramp generator, increases as a function of time to make a given limb move a given distance in a finite amount of time.

Figure 4 shows the block diagram of one such stimulator. Parameters describing the desired waveshape of the ramp-integrator, which controls current intensity to the animal, are passed to a given stimulator by strobing bits 3 through 11 of the Linc-8 accumulator into a separate buffer register for each stimulator. That is, though the accumulator bits are common to all stimulators, the strobe pulse is unique to a given stimulator. From then on the stimulator operates independently of the computer. This has the advantage of

![Block diagram of one complete stimulator. AC3 to AC11 on the top left are the inputs (0 or 1) from the Linc-8 accumulator, which controls the operation of the stimulator. See text for explanation of components.](attachment:image.png)
TABLE 1

Significance of Bits of Linc-8 Computer for Controlling Integrator Input and Output of Programmed Brain Stimulator

<table>
<thead>
<tr>
<th>Bit number</th>
<th>Not set = 0</th>
<th>Set = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Hold integrator at maximum current; provide ramp function only</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Do not reset integrator</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Disable channel</td>
<td>Enable channel</td>
</tr>
<tr>
<td>6</td>
<td>Maximum current; see table 2 for octal code specifying value</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Time (in seconds) to reach maximum current; see table 2 for octal code.</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

leaving the computer free to address another stimulator or for other calculations. But it also means that the maximum amount of current the animal will receive, and the amount of time for the current to reach that maximum, must be specified in the 9-bits sent the stimulator from the Linc-8 accumulator.

To illustrate the design and operation of a stimulator, table 1 gives the significance of the accumulator bits, while table 2 gives the maximum current and time to reach maximum (supplied the stimulator by bits 6 to 11). Bits 3, 4 and 5, when set or not set, control the ramp-generating integrator. The output of the integrator is applied to a MOS switch, which either switches at a rate of 250 pps or is turned off, depending on the control logic. The output of the switch is applied to a voltage-to-current circuit, which is the current generator supplying pulses to the animal. Thus, WHEN the integrator is reset, AND the integrator is allowed to charge to a maximum in a certain amount of time, AND the output control is enabled, THEN 1.0-msec pulses of increasing current intensity are delivered to the animal at 250 pps. The logic conditions imposed by these three bits are: (1) The integrator is reset when B4 is 1 AND the 2-ms multivibrator is 1. (2) The integrator charging is enabled when: (a) A positive slope is selected (Time 0-6, table 2), AND the integrator output is less than the maximum setting, OR (b) A negative slope is selected (Time 7, table 2), AND the integrator output is greater than zero. (3) The output control is disabled (no output) when: (a) The integrator output is less than zero, OR (b) The disable bit is set (B5 = 0), OR (c) Bit 3 is 1 (ramp only) AND the maximum is reached, OR (d) The maximum time (~ 12 seconds) is exceeded without receiving a new command.

In order to control the maximum amount of current and the time to reach maximum, separate MOS multiplex switches are used on the stimulator board. As shown in figure 4, bits 6, 7 and 8 are applied to an 8-channel MOS decoder, multiplex switch. This in effect connects a tap on a precision voltage divider to one terminal of a comparator (Comparator 1). Another comparator terminal is connected to the integrator’s output and hence this comparator senses when the integrator output reaches the desired maximum; that is, when it reaches the voltage on the selected divider tap. The output of the maximum selector multiplex switch is applied through an inverter and a series of resistors to the second multiplex switch. This second switch is controlled by bits 9, 10 and 11, which select the resistor to be connected to the integrator and hence control the charging rate of the integrator. Since the integrator inverts the signal, the negative input voltage causes a positive integrator output. A single positive input can be selected (R8) for

TABLE 2

Octal Computer Codes for Specifying Maximum Stimulating Current and the Time to Reach Maximum

<table>
<thead>
<tr>
<th>Octal code</th>
<th>Maximum current (uA)</th>
<th>Time to reach maximum current (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>50</td>
<td>7</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>750</td>
<td>0.2</td>
</tr>
<tr>
<td>7</td>
<td>1,000</td>
<td>-0.5*</td>
</tr>
</tbody>
</table>

*The last time is for a negative integrator charging rate and is actually the time to reach zero from any maximum.
the rare case when a negative ramp is desired (the last "time" in table 2 with octal Code 7). Because the desired maximum is applied as an input, the time to reach maximum is independent of the maximum value and hence completely controlled by the value of the selected resistor. There is a disable input on the time selector multiplex switch which is, in effect, a ninth open-circuit position for the switch. When disabled, integrator charging is stopped and the integrator output remains at a constant level.

The strobe pulse which loads the LINC accumulator bits also triggers a 2-ms monostable multivibrator (MMV) which in turn triggers a 12-second MMV. The first MMV is used in conjunction with the logic circuits described earlier, to reset the integrator and to disable the output control during resetting. The 12-second MMV is a safety feature which turns off the stimulator after 12 seconds if no new commands are received. Both MMV's are completely resettable; that is, they measure time from the last pulse received. Hence, new commands may be given at any time and the stimulator will correctly accept the new states.

Computer Programming and Control

The time of occurrence of each stimulator relative to other stimulators, and the rate at which current intensity of the output pulses increases with time, are determined by the Linc-8 computer and the software to operate the system. The Linc-8 actually consists of two computers that work in conjunction: a PDP/8 computer that operates either independently or as a control unit, and a Line computer that operates as a peripheral device of the PDP/8. The Linc is dependent upon the PDP/8 for software interpretations of many of its console functions and operations. The electrostimulators are under the control of a Linc-8 program called Programmed Control of the Brain, or PCB. Due to the system configuration just explained, some portions of PCB are written in Linc machine language and others in PDP/8 machine language. However, PCB is logically a single program and can be described as such.

From a computational point of view, the program control of stimulators for inducing coordinated movement is simply the transmission of information to multiple peripheral devices as a function of real-time. The user must specify which electrostimulators are to be turned on, with what current, and at what time. This information is encoded in a table format, called TIMETABLE, and all the running program must do is monitor a real-time clock and strobe information into the stimulator buffers at the time specified by TIMETABLE. The control of the stimulators is completely determined by the values encoded in the TIMETABLE: PCB has no on-line feedback capability, and any modification of output must be done by writing a more precise TIMETABLE. The advantage of this system is that it is compatible with various configurations of stimulators, various movements, and various implantation sites. Moreover, once a particular configuration of hardware and TIMETABLE values is shown to be effective for a certain evoked movement, the TIMETABLE can be stored on magnetic tape for future use. This permits PCB to develop a repertoire of control programs for various movements.

Because PCB derives its versatility from its TIMETABLE repertoire, TIMETABLES have been made as easy to write as possible. PCB possesses teletype input routines that accept information for a TIMETABLE one line at a time, where a "line" is defined as the real-time interval that is to pass before the next stimulator is to be addressed, the particular stimulator channel, and a 9-bit data word specifying what the stimulator is to do. Lines of data can be added, inserted, or removed from the table independently of each other, and the whole TIMETABLE can be coded more efficiently to save space in core storage. PCB is integrated with the Linc systems programs to permit the easy storage of TIMETABLES on magnetic tape and the reading of tape files into core for modification or execution. In addition
to provisions for both teletype and magnetic tape input of TIMETABLES, PCB has a manual control option that enables the user to control the stimulators without a TIMETABLE via the teletype and sense switches on the computer console. This is useful in testing the peripheral equipment and in establishing values for new TIMETABLES.

The Programmed Brain Stimulators are interfaced with the Linc-8 computer with DEC R and W series Flipchip Modules (fig. 5). The PDP-8 accumulator (used to program the stimulators) is converted from DEC logic levels of —3 volts and ground to the ground and +5 volt levels used in the stimulator circuitry. Bits 3 to 11 of the buffered output from the accumulator are led in parallel into W601 positive output converters. The converter outputs are then fed by cables to inverting drivers on the stimulator rack, while the driver outputs are bussed to the input buffers of all the stimulators. These converted accumulator bits are then strobed, in parallel, into any given stimulator buffer by a control pulse decoded and level converted in the interface. Standard DEC IOT (input/output) pulses are used as the control pulses and are produced in W103 device selectors by IOT instructions. Each stimulator has a specific IOT instruction associated with it that upon execution loads the accumulator bits into the input buffer of that stimulator. A separate IOT instruction is combined with the power clear line from the computer, to disable all stimulators in an emergency. This “safety stop” can be instituted from the computer or from a panic button on the stimulator rack.

**Use of the Brain Prosthesis and Limitations**

In practice, the system works like this (see figs. 3, 4, and 5). A monkey with multiple implanted electrodes, each of which when electrically stimulated produces a consistent motor movement of a limb paralyzed to voluntary control, is connected by cable to the Programmed Brain Stimulator. Previously, each electrode was tested by a single stimulator to determine the frequency of stimulation and the maximum current required for production of a given amount of movement. When it is known which of any 10 or fewer electrodes are to be used to produce a given sequence of movements, when each electrode is to be stimulated relative to all other electrodes, the maximum current to be supplied each electrode, and how long it should take to reach the maximum current, then all of this information is supplied TIMETABLE via the teletype of the computer. The control portion of the PCB program running the stimulators is called forth, and when the “Start” button is pressed the animal will be stimulated and the types and amount of movement programmed will occur. Note that with a little training the animal can be given a set of switches that tell the computer what set of movements to produce; thus, he can enter into the control of his own behavior.

Details of actual programs of stimulation to produce purposeful movements have been described elsewhere. These include causing the paralyzed limb to reach out, grasp an object (such as food), and bring the object rapidly and smoothly to its mouth. Or, with different sequences of stimulation, an extension outward and upward (e.g., fig. 3) as in reaching or climbing; or, with a third sequence, extension of the arm backward over the body with a back-and-forth movement (as in scratching) at the base of the tail.

Obviously, development of the experimental brain prosthesis is not complete. For example, there is still much to be done in working out all of the possible combinations of stimulation, for, with as few as three to four electrodes, the permutations and combinations possible to produce goal-directed behavior in a single limb take many hours to investigate. In addition, we are exploring the possibility that “normal” voluntary movement control can be restored to other areas of the diseased or injured cortex. To attempt this, margins of cortex around the injured portion will be stimulated in conjunction with the stimulation of the brain stem, with the hope that by associated stimulation this tissue will “take over” the functions of the portion of cortex lost by the injury or disease.

**Conclusions**

In this report we have given details of a successful brain prosthesis for simulated stroke in monkeys. While much remains to be done for application to stroke, we believe the methods employed may be extended to many other forms of deficit due to brain injury or disease. For example, three other deficits in...
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which we are just now beginning to research as likely candidates are problems of retinal blindness, problems of consciousness, as in coma, and mental retardation. 21, 24

For many critics, the greatest objections to application of our experimental brain prosthetic system to human use will undoubtedly be the relatively high cost, the impracticality of large computers for individual use, and the necessity for implanted electrodes. Costs, like anything else, can only be reduced for a user by subsidization or mass production. If our system should, in time, prove practical for human use, subsidization is a likely prospect from public clinics and national health organizations. Meanwhile, advances in computer hardware miniaturization (such as for space flight), and other electronic techniques, should ultimately lead to practical, relatively low-cost, general-purpose computers small enough to be worn or carried by a human being as part of his clothing. Finally, the use of implanted electrodes in humans, while not desirable, is nevertheless becoming more and more acceptable as this becomes a more widely used practice in the treatment of several neurological and mental diseases. 25, 26 Certainly for the stroke or blind victim, implanted electrodes may well be the lesser evil if it means restoration of his lost function. However, even the necessity of implanted electrodes will probably pass, for experiments in our laboratory, and those of others, show that it may be possible to stimulate selective locations deeply in the brain using external electrodes without the intervention of any surgery. Should this become possible, brain prosthesis may well be used for other types of deficits than those produced by injury or disease, including disorders of behavior.

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