The Journal of Bone and Joint Surgery

American Volume

VOLUME 64-A, No. 1 JANUARY 1982

Long-Term Pain Control by Direct Peripheral-Nerve Stimulation*

BY BLAINE S. NASHOLD, JR., M.D.†, J. LEONARD GOLDNER, M.D.†, JOHN B. MULLEN, M.D.†, AND DONALD S. BRIGHT, M.D.‡, DURHAM, NORTH CAROLINA

From the Department of Surgery, Divisions of Neurosurgery and Orthopaedic Surgery, Duke University Medical Center, Durham

ABSTRACT: **In 1970, we began implanting electrodes for prolonged stimulation of injured peripheral nerves to reduce chronic pain. Thirty-eight peripheral nerves in thirty-five patients have been stimulated with electrodes for a period ranging from four to nine years. Nineteen electrode systems were implanted in the upper extremity (eleven on the median nerve, six on the ulnar nerve, one on the median and ulnar nerves, and one on the median and radial nerves), with successful relief of pain in 52.6 per cent of the patients. Sixteen stimulators have been implanted on the sciatic nerve with a success rate for pain relief of 31 per cent. Failures in the lower extremity were found primarily in lesions of the posterior tibial nerve at the ankle. We speculate that the stress of weight-bearing and the anatomical position of the posterior tibial nerve may partially account for this rate of failure. Use of the electrode-implant system requires careful preoperative assessment by an experienced team, meticulous technique, and a mechanical system that tolerates stress. The location and characteristics of the lesion affect the response to electrical stimulation.**

In 1967, Sweet and Wall implanted electrodes on the median and ulnar nerves of a patient with traumatic neuropathy [18]. Stimulation of the median nerve produced a "pleasant tingling" in the patient's fingers, followed by subsidence of the burning pain. This first surgical experiment to relieve pain by electrical stimulation of a peripheral nerve closely followed publication of the gate-control theory, which postulated that activation of large myelinated nerve fibers might block the transmission of painful impulses in the spinal cord [12]. The formulators of the gate-control theory have since modified their original concept, as physiological data to support it are still in dispute, but their concept served as the basis for new therapies for pain relief through electrical stimulation [1,9,13,15,16]. With technical improvements of the stimulation electrodes and the electronic system, direct electrical stimulation has been applied, with varying degrees of success, to the peripheral nerves, the dorsal column, and the brain in patients with intractable pain.

We are reporting our clinical experience with thirty-five patients whose painful peripheral-nerve lesions were treated by direct electrical stimulation with implanted electrodes, and who have been observed for periods ranging from four to nine years.

Materials and Methods

Nineteen stimulators were implanted on twenty-one peripheral nerves of the upper extremity (single implantations on eleven median and six ulnar nerves and combined implantations on one median-ulnar and one median-radial nerve combination) (Table I). Sixteen patients had implants and stimulation on seventeen sciatic nerves (Table II).

We used an electronic unit (Avery Laboratories,

* Read in part at the Annual Meeting of The American Orthopaedic Association, San Francisco, California, June 12, 1974.

† Duke University Medical Center, Durham, North Carolina 27710.
‡ 800 Hospital Drive, New Bern, North Carolina 28560.

TABLE I

PATIENTS WITH INJURY TO AN UPPER EXTREMITY

Case	Sex, Age (Yrs.)	Injury	No. of Prior Procedures	Time from Onset of Pain to Implantation (Yrs.)	Nerve(s) Stimulated	Year of Electrode Implantation	Sensory Map	No. of Reops.	Result	Complications
1	M, 50	Gunshot wound, L. arm	1	4	Median	1970	—	1	Failure	
2	F, 60	Crush injury, R. fingers	9	5	Median	1971	—	1	Failure	
3	F, 59	Laceration, L. index finger	13	7	Median	1971	—	0	Success	
4	M, 47	Spontan. hemorrh., R. arm	8	4	Median	1972	—	1	Success	
5	M, 68	Pain, R. hand, after cerv. laminec.	5	4	Median	1972	—	0	Transient success (5 mos.)	
6	M, 43	Traum. amput., R. ring and small fingers	7	5	Ulnar	1972	—	0	Success	
7	F, 67	Laceration, L. wrist	2	5	Ulnar	1973	—	0	Success	
8	M, 60	Gunshot wound, R. forearm	1	4	Median and radial	1974	+	3	Success	
9	M, 60	Laceration, L. index finger	5	4	Median	1974	—	0	Success	
10	F, 52	Fracture, L. dist. radius	2	5/12	Median	1975	+	0	Transient success (3 mos.)	
11	M, 52	Crush injury, R. hand	3	1½	Median and ulnar	1975	+	0	Failure	
12	F, 58	Pain of unknown etiol., R. hand	5	8	Ulnar	1975	+	0	Failure	
13	F, 46	Colles' fracture, R. wrist	4	6	Median	1976	—	5	Success	
14	M, 57	Grease-gun injury, R. thumb	2	2	Median	1976	+	2	Failure	Nerve ischemia
15	M, 52	Gunshot wound, R. forearm	2	2	Median	1977	+	0	Success	
16	M, 54	Crush injury, L. index finger	4	4	Ulnar	1977	+	1	Failure	
17	M, 51	Blunt trauma, L. elbow	3	7	Ulnar	1977	+	0	Success	
18	M, 32	Fracture, L. forearm	2	⅔	Ulnar	1977	+	1	Failure	
19	M, 36	Laceration, R. forearm	1	1	Median	1977	+	0	Failure	

Farmingdale, New York) and electrodes of two types: wraparound electrodes from 1970 to 1976 and button electrodes since 1976.

There were twenty-seven men and eight women, ranging in age from thirty-one to seventy-five years. The pain syndromes had been present for an average of four years; the pain had persisted for fourteen years in one patient. Nearly all of the patients had undergone multiple surgical procedures in unsuccessful attempts to relieve the pain. These included sympathectomy, neurolysis, and cordotomy, with an average of four operations per patient. One man had had thirteen operations.

Preoperative Evaluation

The preoperative evaluation began with a careful history, with particular attention to the mechanism of injury, the length of time elapsed since injury, and prior treatments and tests. Some patients had had amputations for traumatic injuries; others had had a variety of peripheral-nerve injuries. A general physical examination, neurosurgical and orthopaedic assessments, and psychiatric and psychological examinations were carried out. Tests done previously were not repeated if the results were known.

Any additional tests that were performed depended on the site and characteristics of the lesion. For example, an amputee with both a painful stump and painful phantom-limb sensation might have had radiographs of the spine, pelvis, and amputation stump; stress-testing of the proximal joints (to determine whether a peripheral nerve was tethered in soft tissue and affected by stretching); and a differential spinal analgesia block (to determine whether sympathetic-nerve paralysis diminished pain and whether

TABLE II

PATIENTS WITH INJURY TO A LOWER EXTREMITY

Case	Sex, Age (Yrs.)	Injury	No. of Prior Procedures	Time from Onset of Pain to Implantation (Yrs.)	Nerve(s) Stimulated	Year of Electrode Implantation	Sensory Map	No. of Reops.	Result	Complications
20	M, 53	Intramusc. injection, R. hip	2	1	Sciatic	1972	—	0	Failure	
21	M, 44	Below-the-knee amput., bilat.	1	2	Sciatic, bilat.	1972	—	0	Success	
22	M, 75	Crush injury, L. leg and foot	0	6	Sciatic	1972	—	1	Failure	
23	M, 56	Pain, R. foot, after lumbar hemilaminec.	8	14	Sciatic	1972	—	1	Failure	
24	M, 35	Osteomyel., R. knee, after gunshot wound	7	12	Sciatic	1973	—	3	Success	
25	M, 42	Pain, L. leg, after hemilaminec.	2	½	Sciatic	1973	—	0	Failure	
26	M, 36	Fracture-dislocation, R. knee	3	1½	Sciatic	1973	—	0	Success	
27	M, 55	Mult. fractures, R. lower limb	0	3	Sciatic	1974	—	0	Failure	
28	F, 44	Blunt trauma, R. ankle	6	8	Sciatic	1974	+	4	Transient success (6 mos.)	Wound infect.
29	M, 31	Crush injury, L. foot	2	2	Sciatic	1975	+	2	Success	
30	M, 41	Gunshot wound, L. thigh	1	1	Sciatic	1976	+	0	Failure	
31	M, 43	Fracture, L. calcaneus	6	3	Sciatic	1976	+	1	Failure	
32	M, 43	Dislocation, R. hip	1	1	Sciatic	1976	—	1	Success	Wound infect.
33	M, 34	Blunt trauma, R. ankle	3	3	Sciatic	1977	+	1	Failure	
34	M, 38	Fracture, L. ankle	4	2	Sciatic	1977	+	1	Transient success (3 mos.)	
35	F, 44	Herniated nucl. pulposus	11	11	Sciatic	1977	—	1	Failure	

a total motor and sensory blockade would relieve pain). Differential spinal and nerve blocks gave information about vasospasm, the changes in skin temperature being detected by clinical examination and thermography. Nerve percussion tests indicated the sites of pathological afferent impulses. Cervical or lumbar sympathetic-nerve blocks gave information, based on the patient's subjective impression, about the effect on pain of increased blood flow, increased skin temperature, and decreased sweating. A peripheral-nerve block several centimeters proximal to the site of a painful neuroma might produce total, partial, or no relief of the major complaint of pain. A supplemental local anesthetic agent also was injected directly into the painful area. If complaints of pain persisted, undiminished, after a nerve block was done on each of two successive days, we thought that an implanted electrode would offer no benefit and no implantation was done.

During the early treatment of pain, care must be taken to identify and relieve any internal or external neural or vascular compression. Primary or secondary sympathetic dystrophy[14] may develop unless such precautions are taken. The use of sympathetic-nerve blocks to diminish vasospasm, intravenous or intra-arterial reserpine to provide several weeks of peripheral vasodilatation, peripheral-nerve blocks for temporary relief of pain, and a trial of transcutaneous electrical stimulation relatively early are important therapeutic procedures that aid in the differential diagnosis and may circumvent the formation of chronic pain syndromes.

Nerve-Block Technique

The painful area is localized by percussion along the course of the peripheral nerve, beginning proximally. Then percussion is repeated, starting distally, to determine whether the zone of pain includes only the major nerve trunk or two or three of its branches as well. The more proximal to the painful area (as determined by percussion) the block is performed, the better will be the chances of

including any aberrant branches crossing from the involved nerve to an adjacent nerve — for example, from the median to the ulnar nerve [7].

A 25-gauge needle is used to inject five milliliters of 1 per cent Xylocaine (lidocaine) around the nerve anteriorly, laterally, medially, and posteriorly, but not directly into it. With the needle adjacent to the nerve, the nerve is stimulated with a peripheral-nerve stimulator to demonstrate its motor function. To determine whether afferent stimuli are carried by both the median and ulnar nerves, the median nerve is blocked first, but the ulnar nerve is blocked only if the median block does not afford complete relief. In the lower extremity, the entire sciatic nerve is blocked high in the thigh to determine whether maximum relief of pain is obtained above the point of branching of the nerve into its posterior tibial and peroneal components. The site of the nerve block must always be far enough proximal to include a crossover from an adjacent main nerve. For this reason we recommend multiple selective blocks [7].

Although no single factor is an absolute guide to success with peripheral-nerve stimulation, the findings that provide the most helpful information about possible benefit are: (1) relief of pain from direct nerve block at a high level, and (2) partial relief of pain during the trial of transcutaneous stimulation. The initial assessment also included an effort to determine whether the pain might be localized to the fibrous or adherent collagen around the joints or tendons instead of from the nerve. Fibrosis of the ligaments of the joint causes vague, dull, and deep nociceptive pain that is different from the paresthesias and hyperesthesias attributable to nerve-root irritation [4].

Selection of Patients

In the course of their assessment, some patients had excisions of peripheral neuromas, even though they had been operated on previously. On several occasions, nerves that were found to be adherent to tendon or bone or compressed by ligamentous or fibrous tissue at the wrist or elbow were treated successfully by neurolysis or by resection, coagulation, or relocation of the remaining nerve. Several patients were thus eliminated as subjects for implantation of electrodes.

After various diagnostic studies and treatment, other groups of patients were eliminated from further consideration for electrical stimulation. These included:

1. Patients in whom the production of a Bernard-Horner syndrome (manifested by a significant increase in skin temperature and a decrease in sweating) by blockade of the cervical stellate ganglion diminished pain. This group was treated by repeated sympathetic-nerve blockade, intra-arterial or intravenous injections of reserpine, and anti-inflammatory medications [6].

2. Patients who improved after injection into joints and connective tissue of a local anesthetic agent or corticosteroids, or both. These patients were treated by the surgical lengthening of soft-tissue contractures and by neurolysis [3]. When the diminution of tension in local tissues and the sympathectomy effect from increased blood flow diminished pain, we thought that use of an electrical stimulator was contraindicated.

3. Patients with combined peripheral-nerve and major vascular injury in whom the pain syndrome was apparently related to diminished blood flow and improved following bypass vein-grafting and sympathectomy. However, many patients in groups 1 and 2 had been treated by sympathectomy previously, but their pain had persisted. As this indicated that decreased blood flow was not the major problem, these patients were retained in the series and received an electrical stimulator.

4. Patients who responded favorably to an occasional peripheral-nerve block with a local anesthetic agent or who benefited from administration of Prolixin (fluphenazine) and Elavil (amitriptyline). We thought that these patients would gain little or no benefit from transcutaneous stimulation. They were treated instead by sural-nerve grafting or nerve resection and bipolar cauterization of the axons within the epineurium. Most of these patients had subsequent diminution of their complaints of hyperpathia, dysesthesia, and hypersensitivity. They also benefited from wearing a protective plastic cap or nylon glove over painful areas of skin, enabling them to tolerate the pain.

5. Patients with chronic compartment syndrome, such as that following dislocation of the knee joint, with severe persistent pain in the foot and leg in spite of restoration of peripheral circulation by bypass vein-grafting. In such syndromes the pain is due to a combination of local trauma and ischemia of the sensory and motor axons and persistent external compression from fibrotic muscles. The same pattern may occur in the forearm. If peripheral circulation is adequate, extensive neurolysis and release of fibrous bands around the peripheral nerves, lengthening of contracted tendons, and excision of fibrotic muscle may produce dramatic relief of pain [3]. The degree of sensory recovery will depend on the degree of nerve injury. Should vasospasm persist, sympathetic blockade may improve peripheral circulation and decrease pain. Intra-arterial or intravenous reserpine has been helpful in reducing vasospasm and in temporarily maintaining warmth in the hand or foot, as with patients in group 1.

The pain syndromes treated in our series varied considerably (Tables I and II). The more complex the injury and the greater the duration of the pain syndrome, the more difficult will be the elimination of the pain. The type of pain may differ for each type of injury, depending on the tissue system involved. The following pain syndromes must be evaluated before use of the peripheral-nerve stimulator is considered: (1) pain after laceration of a digital nerve, (2) pain due to compression of the median nerve at the wrist by the transverse retinacular ligament, (3) pain associated with thrombosis of the ulnar artery at the level of the wrist, (4) pain caused by a combination of neural injury and arterial insufficiency, (5) phantom pain in the amputee, (6) pain in an extremity associated with nerve-root irritation, and (7) pain associated with herpes zoster.

Tests that may be used to assess the possible vascular element of pain include the sweat test, plethysmography, measurements of skin temperature, body-cooling studies, dynamic technetium scans, thermography, Doppler determinations, and arteriography. All of these studies may indicate whether there is a vasospastic component to the pain or if an actual mechanical diminution of blood flow is present.

Finally, an important part of the initial evaluation is a clinical psychological and psychiatric examination to provide information about the patient's response to pain, the possibilities of a conversion reaction or hypochondriasis, and the probability of slow recovery after any surgical procedure. Results of such studies were considered in our final determination of whether a particular patient should undergo implantation therapy. Social problems and secondary-gain factors were identified occasionally and had to be related to the severity of the pain and the prognosis of recovery[2].

In summary, then, the candidates for electrode implantation were those patients who had had a detailed assessment, failure of prior forms of therapy, and primary nerve pain or combined neurovascular pain uncontrolled by other methods of treatment.

Surgical Technique of Electrode Implantation

The operation is performed under local infiltration anesthesia using 1 per cent Xylocaine (lidocaine). Patient cooperation is essential for localization of those nerve funiculi that increase or decrease the pain during electrical stimulation of the peripheral nerve and during nerve-mapping of the funiculi and subsequent intraoperative neural stimulation. As the nerve is exposed in the proximal part of the arm or thigh, well proximal to the area of nerve injury, use of a tourniquet is not feasible. Subcutaneous tunneling into the prepectoral or gluteal area or the lateral region of the thigh will be necessary for placement of the receiver. An anesthetist is in attendance to provide additional analgesia if necessary and to reassure the patient. Patients selected to receive this form of therapy are accustomed to chronic painful sensations and, with appropriate preoperative explanation and judicious use of a local anesthetic, they usually bear the electrical stimulation tests with only minor complaints. Local anesthetic must not be injected into or directly around the nerve, as this will interfere with the mapping. A bipolar cautery is used for hemostasis of small vessels adjacent to the nerve.

Exposure of the median, ulnar, radial, and sciatic nerves is accomplished by following anatomical structures and planes. In exploring the median nerve, the brachial artery is identified, with the median nerve lying anterolateral to it. The ulnar nerve is found lying anteromedial to the brachial artery and is accompanied by the superior collateral branch of this vessel. The radial nerve is isolated medial to the brachioradial muscle and is followed proximally into the triceps muscle. The sciatic nerve may be isolated after identification and retraction of the posterior femoral cutaneous nerve from the sacral plexus; isolation and dissection should be at a point between the semitendinosus and the biceps femoris, just distal to the ischial tuberosity. Care must be exercised to avoid the nerve to the long head of the biceps muscle, which courses from the medial aspect of the sciatic nerve across the nerve and laterally into the belly of the muscle.

Nerve-Mapping by Electrical Stimulation

Nerve-mapping serves to identify the sensory fascicles supplying the painful area, and it is over these fascicles that the stimulating electrodes will be sutured[5,6,17]. Mapping of individual nerves must be done in each patient. As Sunderland has pointed out, the orientation and position of the peripheral nerve fascicles vary constantly within the nerve trunk as they course down the nerve, and therefore one cannot depend on a predetermined, standardized anatomical nerve map. If two nerves are involved, both must be stimulated. Stimulation of the nerve below the level of the origin of pain will fail to produce relief[1]. Three of our patients (Cases 20, 32, and 35) continued to have pain in the lower extremity; the site of electrical stimulation in the mid-part of the thigh was apparently distal to the lesion that was causing the pain, and they failed to gain relief.

With the use of an operating microscope or a 2.5 or a 3.5-magnification loupe, the nerve fascicles are identified and isolated. Neural topography is determined and

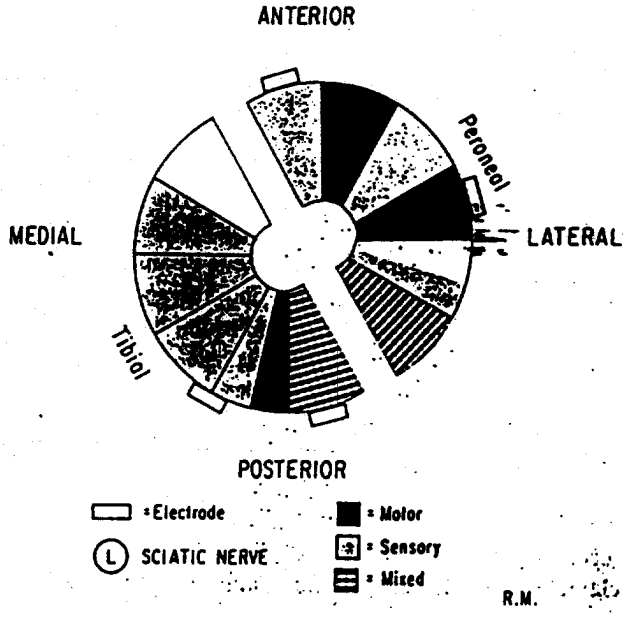

FIG. 1

Case 34. This diagram represents a completed nerve map of the left sciatic nerve. While the topography of the nerve is being determined, the patient is assumed to be in the supine position. The anterior aspect of the nerve corresponds to twelve o'clock and the posterior aspect of the nerve corresponds to six o'clock. The cross section of the nerve is observed in a clockwise fashion. For the left sciatic nerve, the lateral aspect corresponds to three o'clock; the posterior aspect, to six o'clock; and the medial aspect, to nine o'clock. This map was prepared while the patient was awake, and a local anesthetic was used for the incision and dissection.

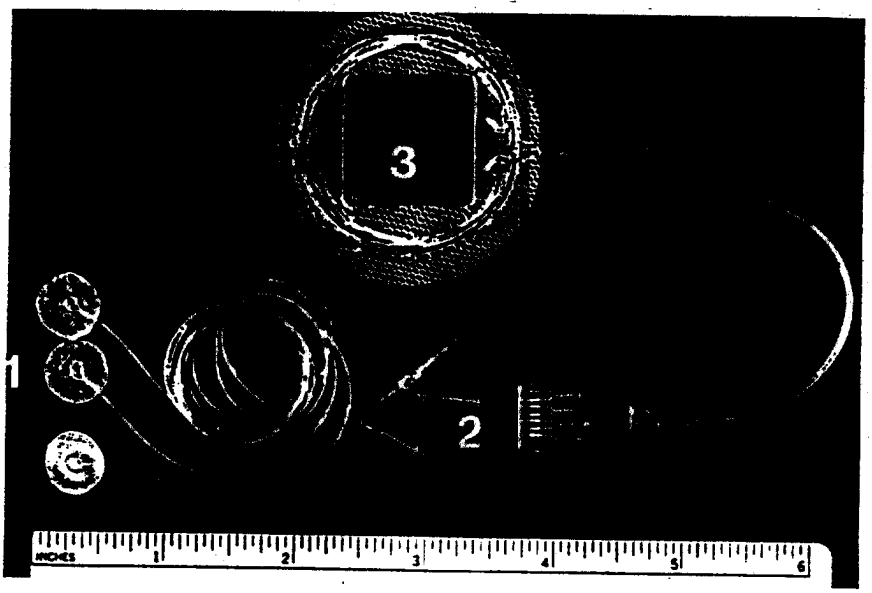

FIG. 2

Components of the implantable electrodes and receiver: (1) button electrodes made of platinum-iridium are superior to the older wrap-around electrodes; (2) the connector between the wires from the electrodes to the receiver — all of these attachments are subcutaneous; and (3) a radio-frequency receiver is sutured over the pectoral muscle or the lateral aspect of the thigh in a subcutaneous pocket.

the nerve map is diagrammed from a perspective facing the axilla, with the exposed proximal end of the nerve oriented clockwise. A fine nylon suture is placed in the epineurium at the twelve o'clock position, to represent the anterior (ventral) aspect of the median nerve. The nerve stimulator (Grass Instruments, Quincy, Massachusetts) is used to determine a one-millisecond biphasic square wave pulse through the bipolar stainless-steel electrodes, which are applied to each funiculus or group of fascicles. The rate of stimulation ranges from one to thirty-three hertz. The patient's motor and sensory responses are observed and recorded on the diagrammatic map, showing the organization of the nerve fascicles constituting the nerve trunk (Fig. 1). Button electrodes are then sutured with 7-0 nylon directly to the epineurium overlying those sensory fascicles which, when stimulated, aggravate the patient's pain. Two to four button electrodes may be sutured onto the peripheral nerve (two electrodes for the median and radial nerves, three or four for the sciatic nerve) (Fig. 2). At each step during implantation, the electrical system is checked to ensure that the stimulation paresthesias are referred into the painful area identified by the patient. Before closing the wound, the electrode systems are connected to lead-out wires (Fig. 3) and led subcutaneously to a radio-frequency receiver placed in a subcutaneous pocket either below the clavicle, in the lower extremity along the lateral aspect of the proximal part of the thigh, or in the abdominal wall above the anterior iliac crest.

Two days postoperatively, the patient is supplied with a low-power radio-frequency transmitter, tuned to match the receiver, and an antenna is taped onto the skin over the site of the receiver (Fig. 4)[13]. The patient is instructed in the use of the transmitter by a knowledgeable member of the team — senior surgeon, resident surgeon, nurse, technician, or physician's associate (Fig. 5). The stimulation is varied by frequency and by pulse width and

FIG. 3

Case 17. The ulnar nerve is resting on a piece of rubber dam. The electrodes are placed on the segment of the nerve that after electrical testing resulted in improvement of pain while the patient was awake. The wires course from the proximally placed receiver. The electrodes are placed topographically at eleven o'clock, four o'clock, and nine o'clock. Electrodes are sutured to the epineurium with 7-0 nylon.

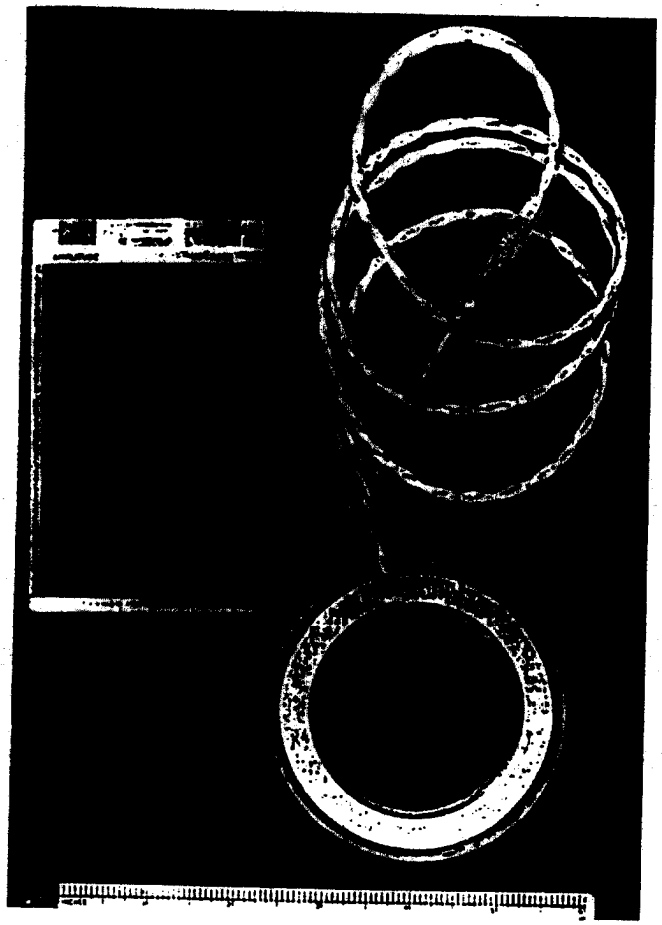

FIG. 4

The radio-frequency transmitter is adjustable for amplitude and rate. The degree of stimulation can be increased or decreased by the patient. The antenna is placed on the skin over the subcutaneous receiver and the connector attaches to the transmitter, which is carried in a holder that is at some convenient location on the trunk or hip region. The antenna is held in place with paper tape.

amplitude until satisfactory stimulation paresthesias are produced in the painful zone. In our experience, the most satisfactory readings for stimulation are those that produce only a threshold sensation of paresthesias, usually at one to two volts and twenty-five to 100 hertz, with a biphasic pulse of 300 milliseconds. These readings are similar to those reported by Long [9,10] and by Picaza et al. Several adjustments of the transmitter indicators may be required for two or three days postoperatively before satisfactory paresthesias are referred into the painful limb.

Results

Case Reports

CASE 4. This patient had a median-nerve stimulator and pain relief for eight years. He was a forty-seven-year-old man who had been receiving Coumadin (warfarin) for a myocardial infarction suffered in 1967, and who had had a spontaneous hemorrhage in the right upper extremity in November 1968. Burning dysesthesia then appeared in the finger tips of the right hand, most severely in the thumb and index finger. Evacuation of the hematoma gave relief of pain for three months. The patient subsequently had seven unsuccessful operations for decompression of the median nerve and release of the scar contracture. In October 1972, five years after the initial occurrence of pain, a median-nerve block was performed, providing complete relief of pain. Psychological evaluation indicated a moderate degree of reactive depression. After implantation of the median-nerve stimulator, the patient had significant relief of pain. Replacement of the stimulator reinstituted control of the pain, and he continued to be free of pain as long as he used the stimulator at regular intervals during the day.

CASE 17. This patient had an ulnar-nerve stimulator and pain relief for three years. He was a fifty-one-year-old man who had chronic pain involving the distribution of the left ulnar nerve after two separate injuries to the left elbow in 1943. Eight years after the original injury, two operations were performed for removal of bone chips and calcium deposits around the elbow, affording significant improvement until 1970, when he was reinjured. Three surgical attempts were made to relieve

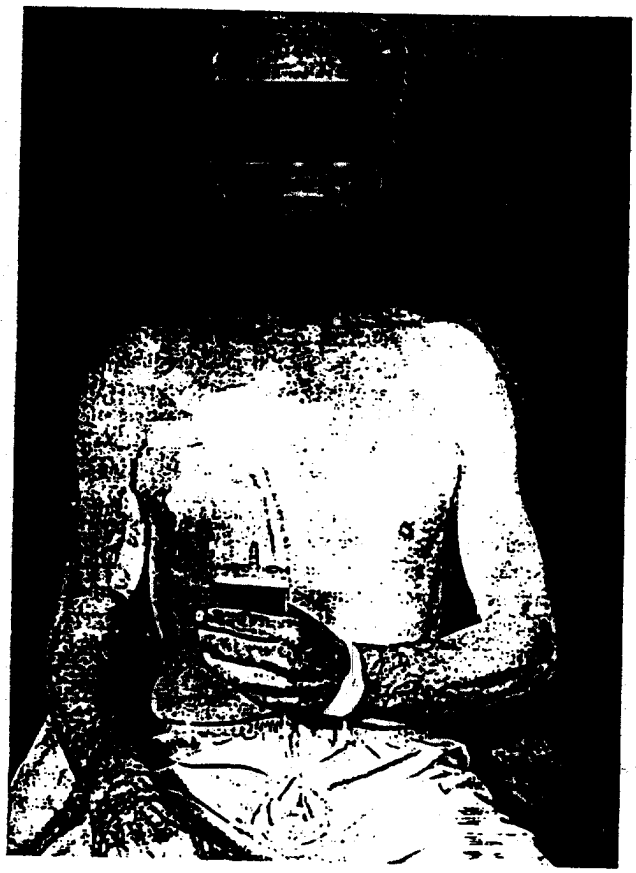

FIG. 5

The patient is holding the radio-frequency transmitter in the hand; the wire courses from the transmitter to the antenna, which is taped to the prepectoral region over the subcutaneous receiver. The incision in the arm is the site of electrode implantation on a peripheral nerve. The patient learns to adjust the amplitude and the rate of the electrical stimulus in order to decrease the painful afferent stimuli and to maintain the level of stimulus at a pre-motor-stimulating intensity. This patient had a chronic ulnar-nerve lesion at the elbow.

pressure on the ulnar nerve, but the patient's symptoms became worse. He complained of paresthesias, burning, and numbness in the digits supplied by the ulnar nerve. Examination of the left hand showed atrophy of the intrinsic muscles innervated by the ulnar nerve and hypersensitivity on palpation from the left elbow to the finger tips. Clinical psychological assessment demonstrated a reactive depression, with no other personality deviations. An axillary brachial block with graduated concentrations of Xylocaine (lidocaine) yielded complete temporary relief of symptoms. In November 1977, a stimulator was implanted on the ulnar nerve in the proximal part of the arm, resulting in complete relief of pain.

CASE 21. This patient had bilateral sciatic-nerve lesions and with stimulators he had pain relief for eight years. He was a forty-four-year-

TABLE III

RELIEF OF PAIN AFTER PERIPHERAL-NERVE STIMULATION

Nerve Stimulated	No. of Patients	Pain Relief		Ratio*
		No.	Per Cent	
Upper extremity	19	10	52.6	10/19
Median nerve	11	5		5/11
Ulnar nerve	6	4		4/6
Median and ulnar nerves	1	0		0/1
Median and radial nerves	1	1		1/1
Lower extremity	16	5	31.2	5/16
Sciatic nerve	16	5		5/16
Total			43	15/35

* Number of patients with pain relief/number of patients in series.

old man who sustained a traumatic bilateral below-the-knee amputation in 1970. Severe bilateral post-traumatic pain and phantom-limb sensations developed, and he was unable to wear artificial limbs because of pain and pressure. A bilateral distal sciatic neurectomy performed in 1971 failed to relieve the painful phantom-limb sensations. Sympathetic-nerve blocks were unsuccessful, but sciatic-nerve blocks produced almost complete relief of pain. Sciatic stimulator electrodes were implanted bilaterally in 1972, affording significant relief of pain in each stump and diminution of the painful phantom-limb sensations. Postoperatively the patient was able to wear prostheses successfully and return to full-time work without medication. At the time of writing, seven years postoperatively, he used the stimulators occasionally, when sitting for a prolonged period of time and as an aid to falling asleep.

CASE 23. This patient had a sciatic nerve and a posterior tibial-nerve stimulator, and no pain relief. She was a fifty-five-year-old woman who was in good health until 1947, when she began having low-back pain radiating to the right lower extremity. Laminectomy and removal of a herniated nucleus pulposus at the fifth lumbar-first sacral interspace relieved the symptoms until 1958, when pain in the right foot recurred. Several operations then were done, including laminectomies, a triple arthrodesis of the right foot, and a lumbar sympathectomy. The patient was examined by us in 1972, at which time results of a neurological examination were normal. Psychiatric assessment revealed no major emotional components to account for her persistent complaints of pain. A sciatic-nerve stimulator was implanted, with minimum relief; five months later the site of the stimulator was changed, with minimum or no relief of pain. In 1973 a dorsal-column stimulator was inserted, with only transient relief. Several months later a cingulotomy was done, with no relief of pain. In December 1974, the patient underwent an anterolateral cordotomy, with temporary relief, but she subsequently became mentally unstable and committed suicide in February 1975.

Summary of Results

Implantation of electrodes for peripheral-nerve stimulation to treat chronic pain of an extremity attributable to peripheral-nerve injury was initiated at Duke University Medical Center in 1970. Our criteria for success were: (1) subjective estimate of more than 90 per cent relief of preoperative pain by electrical stimulation, (2) increased physical activity after implantation, (3) abstinence from analgesic medication, and (4) continued use of the stimulator (Table III).

The duration of pain before implantation ranged from five months to fourteen years, the average being 4.3 years. Individual patients in our series had undergone from zero to thirteen prior operative procedures for attempted relief of pain, with an average of four procedures per patient.

Nineteen stimulators were implanted in the upper extremity (eleven on the median nerve, six on the ulnar nerve, one on the median and ulnar nerves, and one on the median and radial nerves). Pain was relieved following ten of the nineteen implantations, a success rate of 52.6 per cent. In the lower extremity, there were seventeen sciatic-nerve stimulators implanted in sixteen patients (fifteen unilateral and one bilateral) with relief of pain in five patients, a success rate of 31 per cent (Table III). The over-all success rate for long-term control of pain in both the upper and the lower extremity was 43 per cent.

Complications

The rate of complications in patients receiving an implanted stimulator was 8.6 per cent. One patient had ischemia of the median nerve from constriction of the nerve by the cuff electrode, and in two patients superficial wound infections developed after high sciatic-nerve implants. No patient required removal of the implant because of deep infection.

Discussion

An interesting observation from our study is that many patients who continued using electrical stimulation during the entire follow-up period required a shorter duration of stimulation with the passage of time.

In this series, peripheral-nerve stimulation was found to be more effective in the upper extremity than in the lower extremity. Long reported a 17.3 per cent improvement rate after a short-term follow-up[9], but in his long-term study the rate of relief was 50 per cent[1,9,10]. Both figures are less than the improvement rate of 86 per cent reported by Picaza et al. In general, stimulation appeared to be more effective in the upper extremity in all series. The explanation for the lower success rate in the lower extremity may include the following factors.

1. The large sciatic nerve is difficult to stimulate proximally. Certain sensory fascicles deep within the nerve trunk are difficult to activate by electrical stimulation on the surface, where the posterior tibial and peroneal

nerves lie in close approximation. Stimulation may be more effective if the nerves are separated and the fascicles are identified more accurately.

2. Significant failure occurred when there was a lesion of the posterior tibial nerve near the ankle. It is possible that stress from weight-bearing and constant traction on this nerve, the difficulty of protecting it from tethering, compression in the tarsal tunnel, and axial loading forces make the elimination of painful impulses difficult.

We presently believe that the differing rates of success in the three studies mentioned stem from differences in patient selection, location of the lesions, apparatus used, operative technique of localization, method of electrode application, and anatomical variations of motor and sensory-nerve supply to the lesion.

The neural mechanisms of pain relief during electrical stimulation are still unknown. The work of Melzack and Wall, which led to the clinical application of electrical stimulation for the relief of chronic pain in humans [12,18], postulated the existence of a so-called gating mechanism in the dorsal-root entry zone of the spinal cord, which appropriate electrical stimulation of the peripheral nerve would cause to open or close. They theorized that closing of the gate came about through stimulation of the larger myelinated nerve fibers. Others have suggested that relief of pain associated with peripheral-nerve stimulation is due to a peripheral axon blockage along the nerve. Patients often report relief of pain extending beyond the period of actual electrical stimulation, a phenomenon explained by some as being due to the activation of a central mechanism that liberates endogenous morphinometric substances which sustain pain relief after stimulation. All of these intriguing theories must await further clinical and laboratory confirmation.

The high rate of failure of sympathectomy in our group of patients is at variance with the reports of nerve injuries so treated for causalgic pain during World War II [18]. Review of the literature and analysis of the case histories of such patients revealed that the success of sympathectomy is usually predictable. The greatest benefit and highest rate of success are in patients treated relatively early after an injury affecting both the neural and vascular supply to the extremity and in patients with persistent arterial insufficiency and vasospasm. Patients with the fibrotic or third phase of sympathetic-nerve dystrophy (the so-called causalgic syndrome) demonstrated minimum improvement after sympathetic-nerve block or sympathectomy, the pain being due to chronic neural compression and fibrosis [3]. Static vascular insufficiency was not improved significantly by sympathectomy, nor was pain from contracture of collagen in peripheral joints.

Review of a series of more than 200 patients with various aspects of sympathetic dystrophy studied during the past five years [4] brings to light the fact that sympathectomy usually was not necessary for relief of causalgic pain. Many patients had passed the point at which sympathectomy might have helped them; others failed to show abnormal cooling or warming or persistent pain with rapid cooling and, therefore, were not judged to be candidates for sympathectomy.

All of the patients in our series had a specified pain syndrome that was in the chronic phase, whether labeled causalgic or not, and those who had had a sympathectomy did not experience significant relief after sympathetic-nerve block.

Since the advent of vein-grafting, with an increase in the vigor of efforts to re-establish arterial blood flow and improve venous outflow, ischemic difficulties in patients with severely traumatized extremities are less frequent than they were during World War II. In the civilian population, injuries combining vascular and neural damage do not lead to sympathetic dystrophy or so-called true causalgia as frequently as they did twenty years ago, when the only means to preserve the limb were weak collateral arterial circulation, diminished venous outflow, and intact skin flaps augmenting circulation both into and out of the extremity. By our observation, patients who have had replantation of digits or of an entire extremity seldom demonstrate causalgia and sympathetic dystrophy; if these conditions do occur, they appear to be related to diminished arterial input, limited venous outflow, and ischemia of the peripheral nerve and muscle [4].

Nerve block is an important prognostic test for the success of stimulator implantation. We speculate that if nerve block relieves pain, all other factors being ideal, use of the microstimulator will diminish pain; however, if repeated nerve block of one or two nerves does not relieve pain, implantation of a nerve stimulator probably will not help the patient. The nerve block may diminish radiculopathy temporarily by blocking the cumulative effect of sensory input from various points in the extremity, and the clinician must not be misled. Of the patients treated by direct electrical stimulation, all who had temporary relief of pain after nerve block did not necessarily respond to electrical stimulation, but all who were relieved by electrical stimulation had been relieved by peripheral-nerve block. Most patients who were helped by direct electrical stimulation with an implanted electrode also were partially relieved temporarily by transcutaneous stimulation. A patient gaining relief of pain by nerve block but not by the electrical stimulator might have, for example, fibrosis of the flexor tendons, periarticular fibrosis of the finger joints, and tethering of the median nerve by fibrosis of the muscles of the forearm. Such a patient would obtain significant peripheral pain-relief by blocking of the median nerve, by diminution of the afferent impulses from the adherent soft tissue affecting the median nerve. Application of the peripheral-nerve stimulator to the median nerve in this patient would diminish paresthesia and change the characteristics of sensation, but would not alter the pain caused by tension in collagen or by irritation of a joint [4,6].

We believe that rhizotomy and cordotomy have no place in the operative treatment of intractable pain

originating from peripheral-nerve injury. Neurolysis and resection of neuromas may be helpful, but the technique of such procedures is extremely important if relief of pain is to be obtained.

Psychiatric and psychological testing are essential in singling out patients with depression, conversion hysteria, or hypochondriasis[2]. Those patients with conversion and hysterical personality patterns usually have a poor prognosis, even though their pattern of pain may be altered and their need for analgesic medication may be diminished after implantation. No single psychological test is an infallible indicator of potential complications from emotional factors[2]. Clinical psychiatric assessment and clinical psychological testing are complementary; the latter may bring out elements of depression and conversion not readily detectable in a straightforward psychiatric interview. Close cooperation is essential between the psychiatrist, the psychologist, and the surgeon. The surgeon may detect clearly defined organic symptoms requiring treatment, but the psychiatrist may emphasize the hazards of surgical treatment in the patient with a particular personality pattern and emotional profile. The experienced surgeon who works daily with patients suffering from intractable pain will gain an impression of each patient's reliability, the validity of his or her complaints of pain, and the likely response to treatment. All of these are important in the ultimate decision about the form of treatment to be used. The many secondary-gain factors to the patient, such as fear of failure, financial gain, marital conflicts, and employer-employee conflict, may be brought to light. All such factors affect the outcome of the patient's treatment.

Case 23 is a good illustration of the potential for failure in a patient with significant psychiatric problems. This patient's pattern of pain, the recurrence of pain many years after the initial episode, and the multiple sites of treatment (spine and foot) imply the presence of a conversion response and a psychotic element, even though the psychiatrist performing the initial assessment did not detect these possibilities.

Conclusions

In summary, electrical stimulation of peripheral nerves as a means of decreasing pain seems well justified by the results of our study and others over the past fifteen years. This approach to pain relief must include thorough preliminary studies, judicious selection of patients, availability of the necessary equipment for nerve-mapping through direct stimulation of the exposed nerve, and a thorough knowledge of the operative technique of implantation. This is not a casual operation for the occasional operator. We believe that the technique should be used by clinical investigators with experience in the treatment of peripheral-nerve injuries. The proper setting must include a cooperative effort between orthopaedists, neurosurgeons, anesthesiologists, psychiatrists, clinical psychologists, and electrical engineers.

The success rate of peripheral-nerve stimulation should improve with: (1) standardization of criteria for patient selection, which we have better defined as our study has progressed; (2) sensory-nerve mapping and implantation of individual button electrodes over the involved sensory fascicles; (3) early elimination of arterial, venous, and compressive factors that may cause abnormal sensory input; and (4) relatively early use of both transcutaneous and direct electrical stimulation as an adjunct to the therapy already prescribed.

Our results have improved consistently during the course of this study; with ongoing improvements in mechanical systems and methods of patient assessment, future results should be even better.

References

1. Campbell, J. N., and Long, D. M.: Peripheral Nerve Stimulation in the Treatment of Intractable Pain. J. Neurosurg., 45: 692-699, 1976.
2. Gentry, W. D.; Newman, M. C.; Goldner, J. L.; and von Baeyer, Carl: Relation Between Graduated Spinal Block Technique and MMPI for Diagnosis and Prognosis of Chronic Low-Back Pain. Spine, 2: 210-213, 1977.
3. Goldner, J. L.: Volkmann's Ischemic Contracture. *In* Hand Surgery, edited by J. E. Flynn. Ed. 2. Baltimore, Williams and Wilkins, 1975.
4. Goldner, J. L.: Pain: Extremities and Spine — Evaluation and Differential Diagnosis. *In* Peripheral Nerve Problems, pp. 119-175. Edited by G. T. Omer and Morton Spinner. Philadelphia, W. B. Saunders, 1980.
5. Goldner, J. L.: Intra-Operative Motor and Sensory Nerve Mapping. Three Hundred Patients Investigated 1955-1977. Unpublished data.
6. Goldner, J. L., and Hendrix, P. C.: Use of Transcutaneous Electrical Stimulation in the Management of Chronic Pain Syndromes. *In* Current Concepts in the Management of Chronic Pain, pp. 111-125. Edited by P. L. Le Roy. Miami, Florida, Symposia Specialists, 1977.
7. Goldner, J. L., and Jones, W. B.: Anomalous Innervation of the Forearm and the Hand. *In* Proceedings of the American Society for Surgery of the Hand. J. Bone and Joint Surg., 48-A: 604, April 1966.
8. Kraus, W. M., and Ingham, S. D.: Peripheral Nerve Topography. Seventy-seven Observations of Electrical Stimulation of Normal and Diseased Peripheral Nerves. Arch. Neurol. and Psychiat., 4: 259-296, 1920.
9. Long, D. M.: Electrical Stimulation for Relief of Pain from Chronic Nerve Injury. J. Neurosurg., 39: 718-722, 1973.
10. Long, D. M.: External Electrical Stimulation as a Treatment of Chronic Pain. Minneapolis Med., 57: 195-198, 1974.
11. Marie, Pierre; Meige, Henry; and Gosset, A.: Les localisations motrices dans les nerfs peripheriques. Bull. acad. méd., 74: 798-810, 1915.
12. Melzack, Ronald, and Wall, P. D.: Pain Mechanisms: A New Theory. Science, 150: 971-979, 1965.
13. Nashold, B. S., Jr., and Goldner, J. L.: Electrical Stimulation of Peripheral Nerves for Relief of Intractable Chronic Pain. Med. Instrum., 9: 224-225, 1975.
14. Nashold, B. S., Jr.; Goldner, J. L.; and Bright, D. S.: Direct Electrical Stimulation of the Peripheral Nerves for Relief of Intractable Pain. *In* Proceedings of the American Society for Surgery of the Hand. J. Bone and Joint Surg., 57-A: 729, July 1975.
15. Nielson, K. D.; Watts, Clark; and Clark, W. K.: Peripheral Nerve Injury from Implantation of Chronic Stimulating Electrodes for Pain Control. Surg. Neurol., 5: 51-53, 1976.
16. Picaza, J. A.; Cannon, B. W.; Hunter, S. E.; Boyd, A. S.; Guma, J.; and Maurer, D.: Pain Suppression by Peripheral Nerve Stimulation. Part 1. Observations with Transcutaneous Stimuli. Surg. Neurol., 4: 105-114, 1975.
17. Sunderland, Sydney: The Intraneural Topography of the Radial, Median and Ulnar Nerve. Brain, 68: 243-299, 1945.
18. White, J. C., and Sweet, W. H.: Pain and the Neurosurgeon. A Forty Year Experience, pp. 895-896. Springfield, Illinois, Charles C Thomas, 1969.