THE EPINEURAL ELECTRODE: DEVELOPMENT, TESTS AND CLINICAL STUDIES

Thoma,H., Altrichter,C., Girsch,W., Holle,J., Lanmüller,H., Mayr,W.

Vienna University, Vienna, AUSTRIA

ABSTRACT

The electrode is the most sensitive part of implantable systems for functional electrostimulation (FES). The Epineural Electrode (ENE) was developed to achieve a controllable progressive muscle contraction and reduce muscle fatigue during functional electrostimulation. In vitro studies of annular (torus-shaped) electrodes have been carried out to select adequate tantalum), wire diameters (0,15-0,3 mm) and electrode diameters (0,9-1,6 mm). We investigated the long-term stability of ENEs using DC current (range: 1 μA) and different impulse amplitudes (2, 4, 8 Volts) in sheep and rat experiments. Depending upon size and material, ENE tolerates anodic and cathodic impulses of 1 msec and 8 mA (peak current). ENEs were used during clinical application in 4 paraplegic patients (16 channel implants) for stimulation of lower extremities; in 9 quadriplegic patients (8 channel implants); and one patient with Ondines course for diaphragm pacing, for a total observation time of 44 patient years. The low rate of clinical complications, including no corrosion of the electrodes or significant loss of nerve fibers, seems related to the small dimensions of the electrode (1 mm^2).

KEY WORDS: Epineural stimulation, multi-channel implants, FES, phrenic pacemaker, stimulation of lower extremities.

INTRODUCTION

Cuff electrodes are mostly used for stimulation of peripheral nerves (Glenn) (1). Percutaneous intra muscular electrodes (316 stainless steel) were developed and used in various applications by Mortimer, Peckham and Marsolais (2). A multiconductor cable (platina iridium) for neurological prostheses with exceptional excellent mechanical properties was developed by Brindleys group (Cooper, 3).

To realize the idea of "roundabout electrode" for reduction of electrically induced fatigue of the neuromuscular system by means of multiple (3-5) electrodes around the peripheral nerve, the development of miniaturized, highly efficient and low cost epineural electrodes (ENE) was necessary (4). To avoid corona effects (local concentration of ions) and to allow easy positioning of the electrodes to the epineurium of the nerve by a suture (8-0 prolene), an annular design of the electrode (stainless steel 316) has chosen (5).

The intention of this paper is (1) to summarize the stepwise development, tests and results of ENE during the last 15 years and (2) to present detailed data of up to now unpublished investigations. The paper is focused to mechanical, electrical and biological properties of ENE.

MATERIAL AND METHODS

One of the basic ideas in ENE design is the use of the same material for the electrode and lead. In the long run of development, the following materials and products were tested:

Materials: stainless steel, platinum iridium, tantalum (niobium)

Products: (1) Avery pacemaker lead, (2) M 612 P / Polyaethylen, (3) Ethicon 611 P 0.15 (7 x 0.05), (4) Fine Wire Comp. Teflon-Clear, 5-316 LMG 0.15 (19 x 0.03), (5) Leico Industries / Teflon, 16557 / 44 T 0.2 (7 x 0.05), 6) Cooper-Cable and (7) Ethicon 612 P 0.2 (12 x 0.05).

To achieve an optimum of bioelectric stability (charge) and dimensions, the following test bank was developed (5): 10 samples of electrode pairs, each in a plastic box filled with saline solution, were loaded by standard impulses of a constant current source (e.g. I=6mA, f=40Hz, impulse duration=0.5ms). Peak voltage, representing the impedance of the electrode arrangement, was measured and printed out every 20 minutes together with date and time, by a personal computer system. The increase of voltage corresponds to corrosion of the electrode. During our design studies, the following parameters of electrode and material were tested: (1) electrode diameter: 0.9 - 1.6 mm, (2) wire diameter: 0.15 - 0.3 mm, (3) filament diameter: 50 / 30μm, (4)turns of the electrode: one or two.

Test conditions: (1) constant current 6 mA, (used range: 0.4 - 2 mA), (2) impulse duration: 500 μs, (3) impulse frequency 40 Hz.

Design of electrode leads

The material and products as listed in the last chapter were mechanically tested by an own developed test machine. The electrode lead under an tension of 150-200 g was inclined every second by a motor driven torque rod up to 90 degrees (5). The present design of ENE is demonstrated in Fig. 1.

In Vivo Investigations

During the last 15 years numerous studies on animals were performed. Different to other investigators we prefer the sheep for studies, because parameters (size, physiology, neuro-electrophysiology) of this animal are much closer to those of humans compared to other standardized animal models e.g. cats.

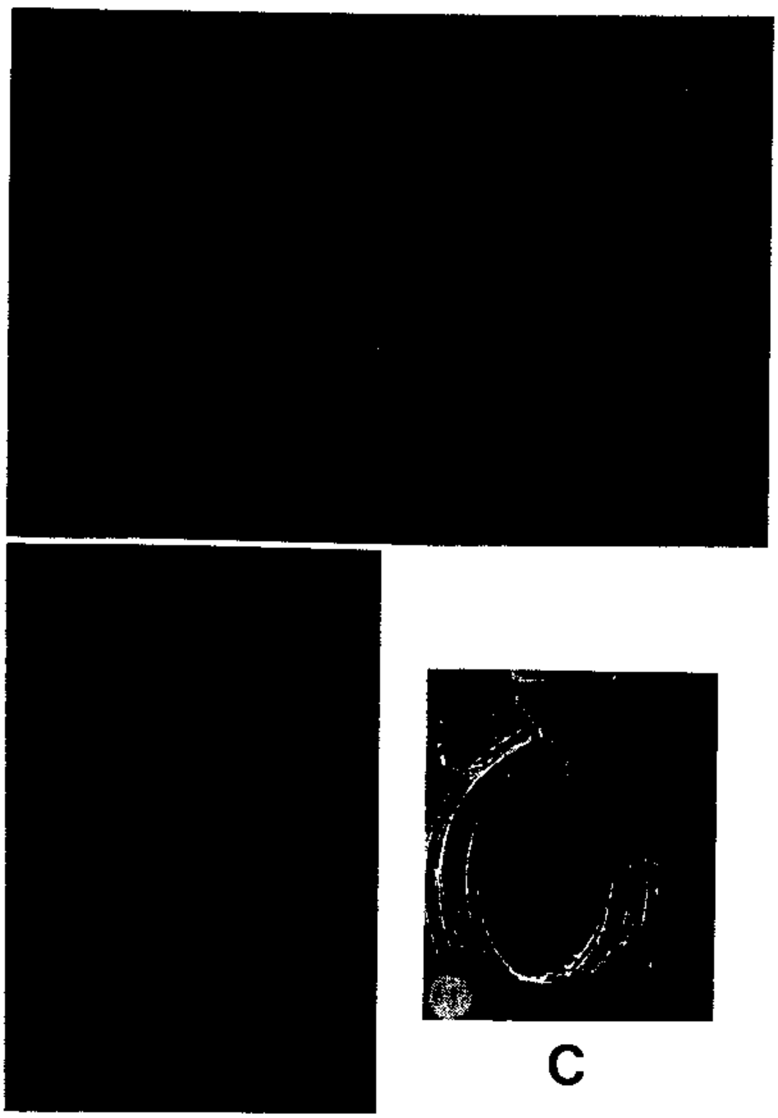

Figure 1. 20-channel implant, electrode lead with ENE. A: 20-channel implant in laser welded niobium encapsulation with connectors, B: Connectors with multicoiled electrode leads (EH 612 P). The lead ends in a distributor from which the single-coiled leads can be extended by the surgeon to the desired place of the nerve, C: Annular electrode tip (ENE), diameter 0,8 mm.

Nerve damage

The main question in the field of nerve stimulation is biocompatibility (no damage of the nerve). The influence of long term application of ENE to the nerve has been investigated twice. D.Rosenkranz of our group performed histologic examination on the ischiatic nerve of 60 rats equipped with a DC current source (1 μA) and two electrodes (Ethicon EH 612 P) ten years ago (6). In a new study 1988 (by W. Girsch) 60 rats were equipped with 4 electrodes each nerve to investigate mechanical stress only. In this study the total area of the nerve is compared to the area of damaged fibres (the study is still running).

Electrode impedance

Electrode impedance of ENE and threshold were measured in 6 sheep experiments lasting one year. 2x5 electrodes were implanted in each animal on different nerves (n.laryng.rec., n.phrenicus, n.femoralis, n.ischiaticus) (7).

Sacral root stimulation

Another study was devoted to sacral root stimulation for continence and micturition by H. Kiesswetter of our group. In 5 female dogs 8-channel systems were implanted, electrodes positioned extradurally to S2-S4 of the cord. Stimulation effects were measured as usual via fluid-filled balloons in the bladder and urethra connected to pressure transducers.

Fatigue studies

Another study was performed by W.Happak of our group to quantify the improvement of function, using multi-channel stimulation (roundabout electrode)(4). The rectus muscle was preparated in 6 anaesthetized sheep on both legs and fixed to a force transducer. Single-and multi-channel stimulation was synchronously turned on to the right and left rectus muscle (or vice versa). Fatigue index (FI) according to Burke (8) was modified for these experiments.

Clinical investigation

Methods and results including gain characteristics during the use of ENE to stimulate lower extremities in paraplegic patients with 16 electrodes as well as the application of 8-channel implants for phrenic stimulation have already been published (7,9).

RESULTS

Preclinical Investigations

Comparing the stainless steel materials SS 316 LMG and EH 611 P it could be evaluated that both materials need 0,8 mm diameter and two turns for permanent stability (Table 1).

	material \ test time (h)	0	50	100	result
	SS316LMG				
1	Ø 0.8 mm	4.6V	6.0V	7.4V	unstable
2	Ø 0.8 mm two turns	3.5V	3.9V	3.9V	stable
3	Ø 1.0 mm	3.7V	5.1V	6.6V	unstable
4	Ø 1.0 mm two turns	3.4V	3.7V	3.7V	stable
	EH611P				
1	Ø 0.6 mm	5.8V	9.3V	9.3V	unstable
2	Ø 0.6 mm two turns	4.9V	5.6V	6.8V	unstable
3	Ø 0.8 mm	5.2V	9.3V	9.3V	unstable
4	Ø 1.0 mm	4.8V	9.3V	9.3V	unstable
5	Ø 0.8 mm two turns	4.4V	4.4V	4.4V	stable

Table 1. ENE in vitro tests, I=6mA, f=40Hz impulse duration: 500 μsec; mean of five probes. Materials: stainless steel SS 316 LMG and EH 611 P

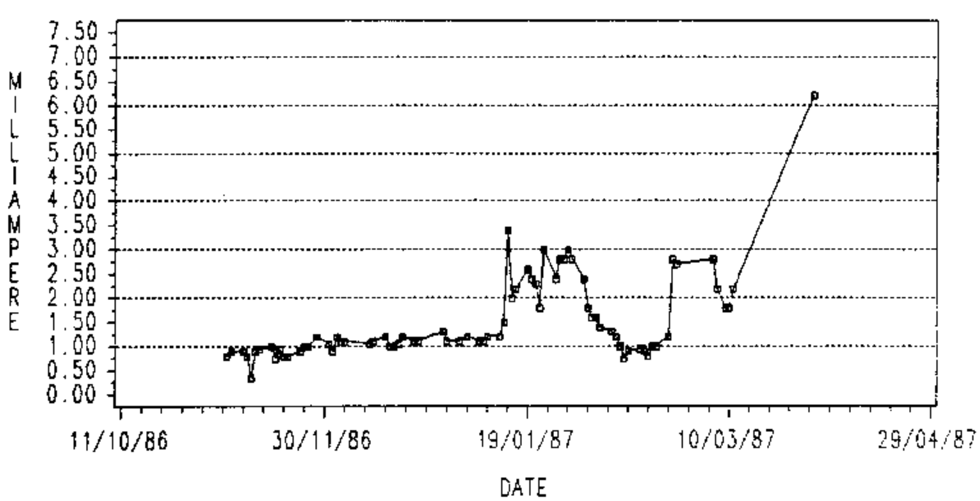

Figure 2. Initial Threshold in sheep (No. 1, electrode 1). Multiple infections lead to increase of the threshold.

Results of mechanical stress to electrode leads depend on material of insulation (column 2 and 3) and tube parameters (Table 2). The Ethicon 611 wire (last column)

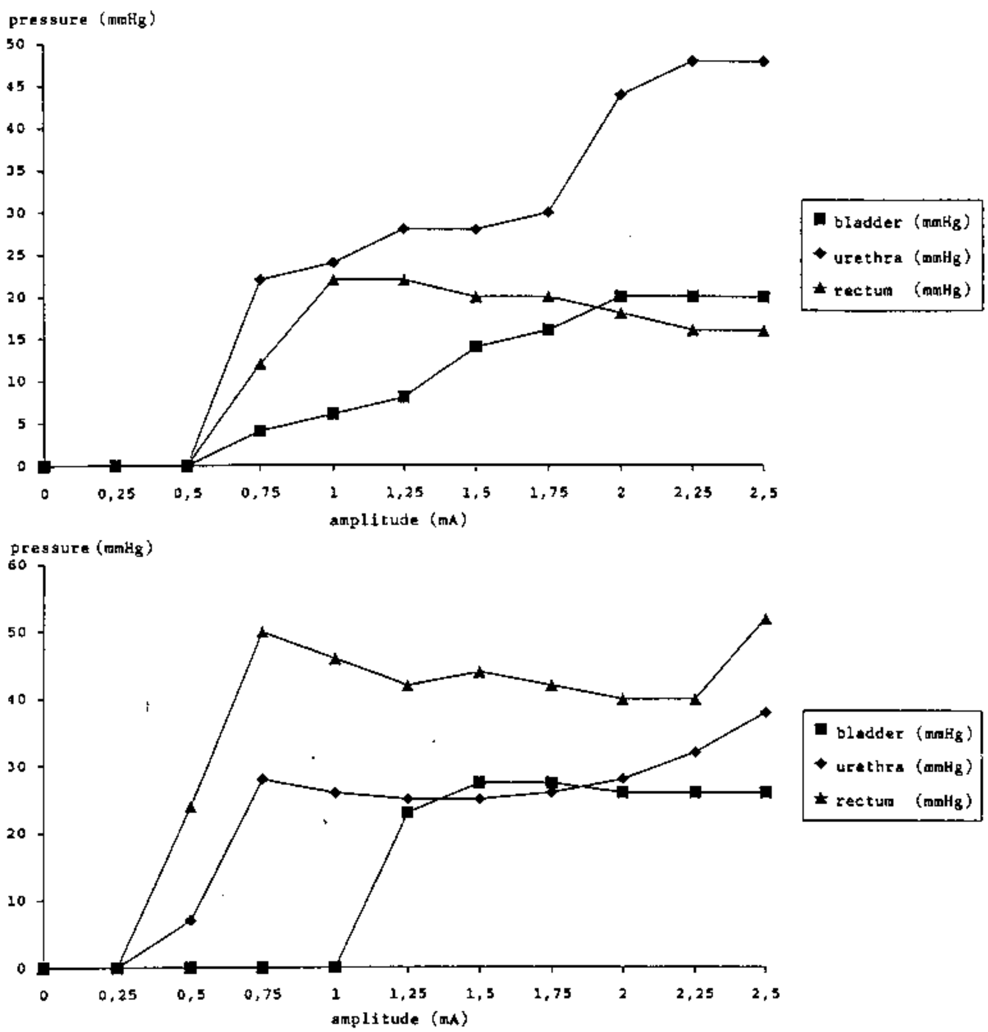

Figure 3. Stimulation current (mA) versus relative pressure (mm Hg)

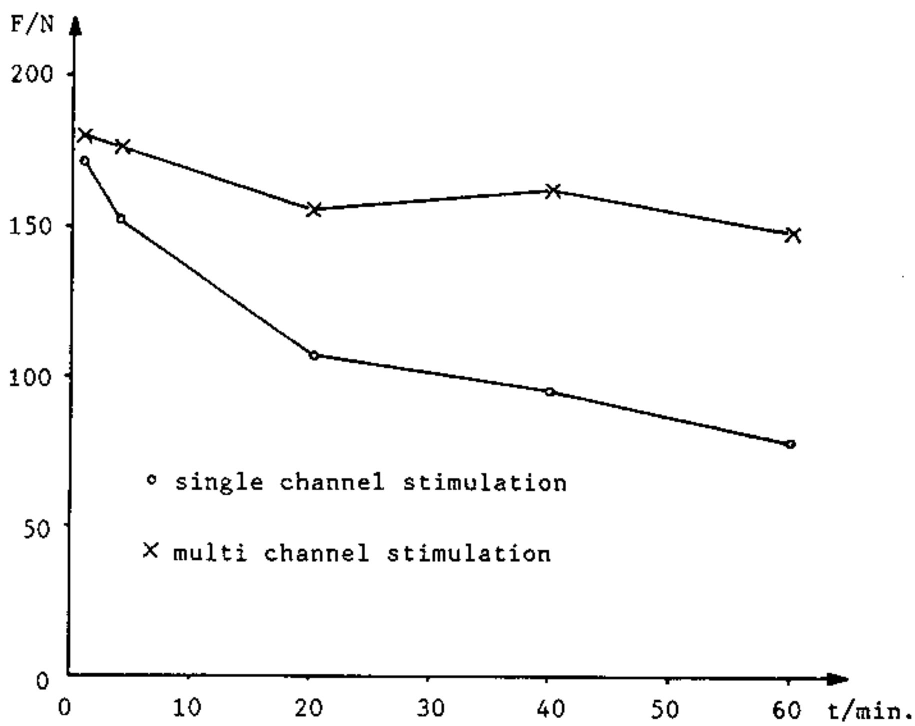

Figure 4. Cyclic isometric contraction of right and left rectus muscle (sheep): stimulation 1 sec, pause 2 sec. Force is in Newton.

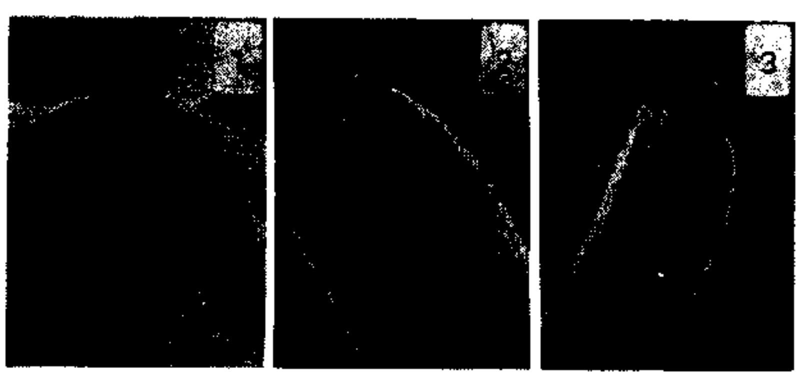

Figure 5. Failure of EH 611 P materials (50 m) due to mechanical stress: 1) unilateral vibration failure; 2) localized corrosion (pitting) crushing tensile failure; 3) ductile tensile crack.

was tested in straight position with relatively good results, but during clinical application this design failed.

During our experiments in sheep for evaluation of initial threshold and impedance of electrodes the mean impedance at the beginning and the end of this study was 900 ± 40 SD to 950 ±SD Ω. The threshold 0.85 ± 0.1 SD to 0.9 ± 0.2 SD mA. Life events, e.g. infections and gravidity, have a significant influence on these values (Fig.2.).

During sacral root stimulation usefulness of selective stimulation could be demonstrated. To avoid simultaneous contraction of sphincter and detrusor muscle, which causes a dangerous reflux to kidneys, different thresholds for stimulation of sphincter and detrusor muscles could be observed in some combinations (Fig.3).

In the experiments of muscle fatigue the Fatigue Index according to Burke (8) decreased from 0.82-0.41 (mean of 5 animals during single channel stimulation), while multi-channel stimulation improved from 0.96 (first minute) to 0.66 (60th min). In Fig.

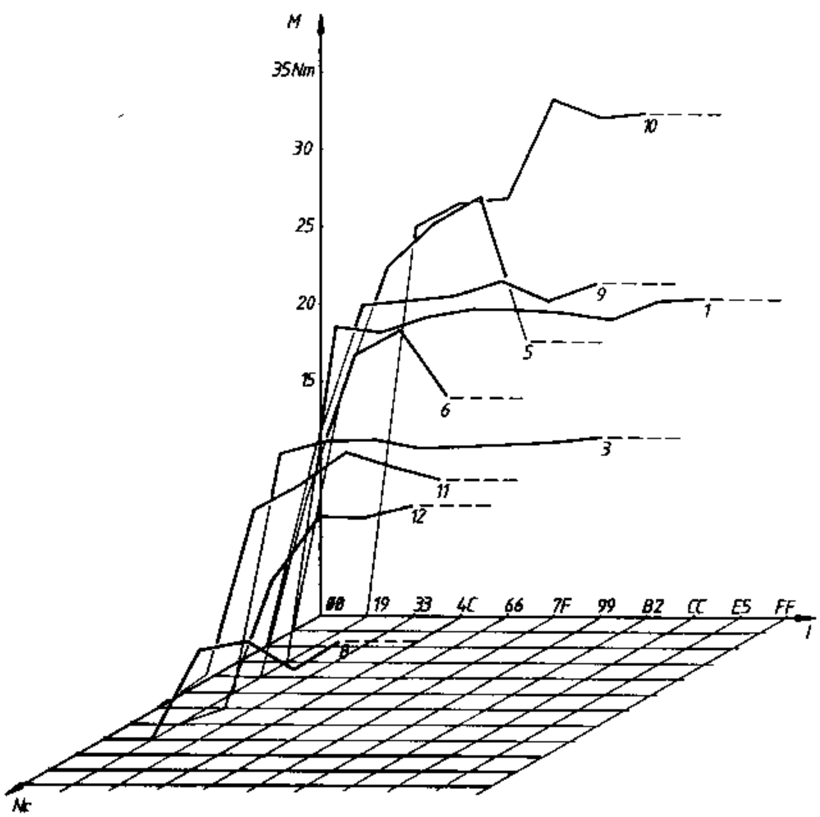

Figure 6. AMPLITUDE GAIN. Date 26.4.1985, patient B.W.,implant Nr.1, amplitude range/(0 to 8 mA) (00 to FF), impulse duration 0,8 ms, frequency 30 Hz, number of impulses 4, stimulated muscle: left quadriceps femoris, angle of knee joint: 90° Y-Axis: torque in Nm, Z-Axis: Number of electrode combination.

4 a typical example of force decrease during single-and multi-channel stimulation is demonstrated.

Clinical Investigations

Basic data of stimulation of 9 quadriplegic patients are summarized in table 3. The mean stimulation current (all combinations of one patient) for the threshold of

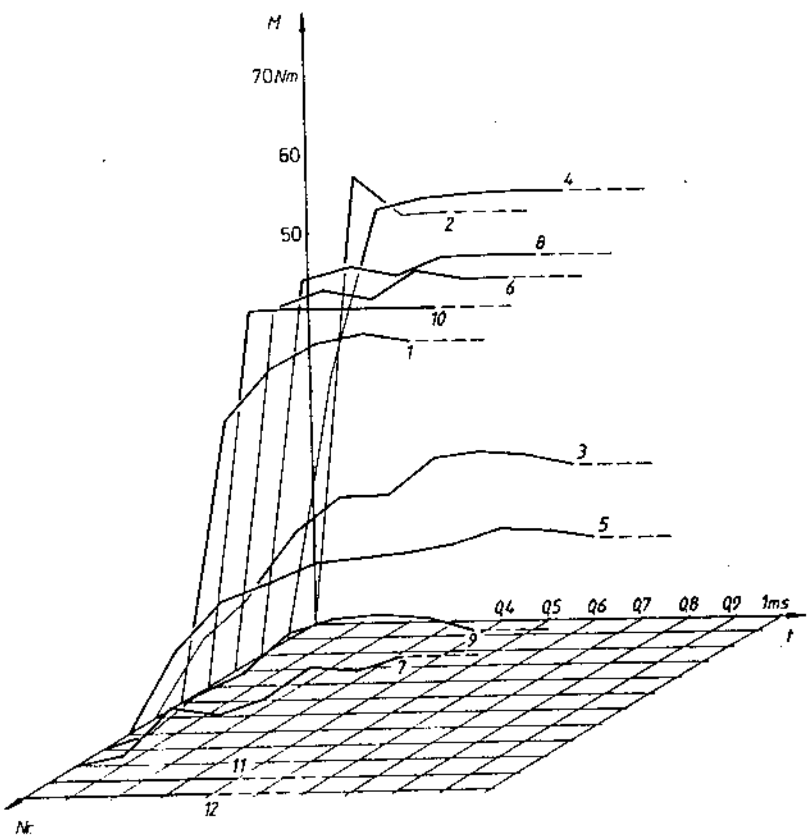

Fig. 7. IMPULSE DURATION GAIN. Date 14.5.1985, patient R.K.,implant Nr.5, amplitude: 8 mA, frequency 30 Hz, number of impulses 4, stimulated muscle: right quadriceps femoris, angle of knee joint: 90°, Y-Axis: torque in Nm ,Z-Axis: Number of electrode combination.

phrenic nerve stimulation is in the range of 0.4 to 1.65 mA, to reach the tidal-volume the mean current varies from 0.65 to 3.5 mA.

Supported by the good results of straight Ethicon 611 P wires we implanted this electrode in a 15 months old girl. 9 months later 5 of the 8 leads had a failure, new electrodes had to be replaced. Results of the electron microscope investigations are demonstrated in Fig. 5. We were surprised, that mechanical stress was the reason to fail.

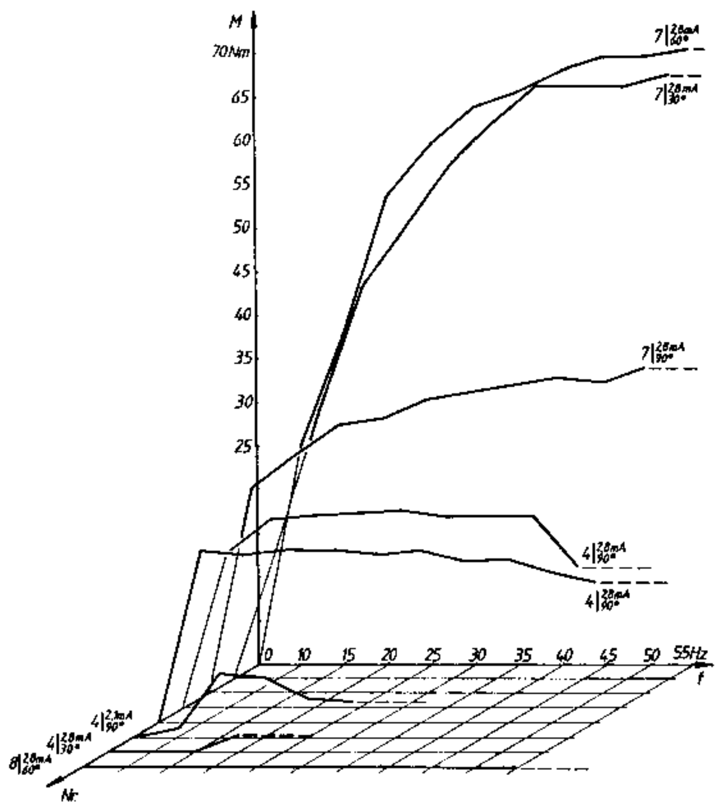

Fig. 8. FREQUENCY GAIN. Date 31.5.1985, patient M.Sch., implant Nr.6, impulse duration 0,5 ms, duration of measuring cycle 500 ms, stimulated muscle: left quadriceps femoris, angle of knee joint: (30°/60°/90°) Y-Axis: torque in Nm, Z-Axis: Number of electrode combination.

ETHICON TYPE	612	612	612	612	612	611
HELIX OUTER DIAMETER MM	1,9	1,9	1,9	1,4	1,5	0
HELIX ANGLE, MM	1,4	5	0,3	1,5	0,3	0
NO. OF ELECTRODE LEADS	4	5	1	1	1	1
TUBE DIAMETER OUTER MM INNER MM	3,18 1,98	3,18 1,98	3,18 1,98	1,96 1,47	3,18 1,57	1,96 1,47
TYPE OF SILICON FILLING	E14	DC734	E41	E43	DC734	E43
INSULATION	PAINT	POLY-ETHYLENE	0	0	0	0
TEST CYCLES	100.000	2.500.000	2.500.000	12.600.000	16.000.000	3.100.000
RESULT	FAILURE	OK	TUBE FAILURE	OK	OK	FAILURE

Material: Ethicon 612P and 611P, 12/7 filaments each 50 µm
Tube material: Dow Corning Silastic 602
Material for filling: E .. Elastosil, Wacker Co, DC .. Dow Corning Co.

Table 2. Stainless steel electrode wires in different configurations: mechanical stress

PATIENT CORD LESION	UD C2/3	JSE C1/2	FF C2/3	UM C2/3	JS C1/2	HU C1/2	MW CO	AR C2/3	HP C2/3
SUPINE POSITION									
THRESHOLD mA	0.4	0.65		0.6	1.25	1.65	0.75	0.39	0.72
TIDALVOLUME mA	0.7	0.9		0.65	2.4	3.0	2.0	0.81	1.5
TIDALV.mean ml/kg	9.6	9.9		12.1	11.4	10.7	11.3	10.6	19.5
SITTING POSITION									
THRESHOLD mA	0.4	0.65	0.8	0.55	1.4	1.12	0.8	0.45	0.68
TIDALVOLUME mA	0.7	0.7	2.9	1.0	3.3	3.5	2.5	0.9	1.8
TIDALV.mean ml/kg	8.1	8.9	3.8	9.2	9.9	8.2	7.9	11.5	10.3
HEIGHT cm	185	180	174	180	190	156	160	196	174
WEIGHT kg	80	95	80	70	70	35	35	70	75
RESP.RATE per min	13	12-13	17	10-13	12-14	14-15	13-17	12-14	11-12
INSP.DURATION	1.2	1.2	1.1	1.0	1.2	1.2	1.2	1.3	1.3

Table 3. Basic clinical data of 9 quadruplegic patients with phrenic pacemaker

Gain characteristics of quadriceps stimulation during the program of stimulation of lower extremities are demonstrated in Figures. 6-8. At this time no operation microscope and more rigid electrode leads were used. Therefore, thresholds are higher compared to our phrenic pacemaker application.

DISCUSSION

Main reasons to reject platina-iridium concern costs and mechanic quality. Not even the electric efficiency (charge/mm^2) is better compared to the oxide surface of stainless steel. Tantal and niobium were rejected because of the very complex processing and high electrical impedance. We made efforts to reduce filament diameter from 50 to 30 m or less, but these products (e.g. Fine Wire Company) are still too elastic compared to Ethicon wires. High ductility of the electrode can be fixed during surgery without any stress (tension) to the nerve.

Requirements for implementation and use of the roundabout electrode are: 1) four electrodes around the nerve; 2) close positioning to the nerve fibers (epineural placement); 3) submaximum stimulation; and 4) a special electronic circuit for switching the electrodes. The disadvantages of greater expenditure of hardware and software and the necessity to use an operation microscope during surgery are compensated for by the advantages of 1) equal loading of muscle fibers resulting in less fatigue; 2) excellent recruitment characteristics (gain); and 3) electrode redundancy. For example, our patient with broken electrode leads could be adequately stimulated with the remaining three electrodes.

Our experience in stimulation of lower extremities can be summarized as follows:

- *Using the "roundabout electrode", we can achieve smooth but strong motion of the extremities implanting 4 or more electrodes fixed directly to the epineurium with a thin atraumatic suture.*
- *A well positioned electrode needs a maximum of 3 mA peak current for sufficient stimulation.*
- *In contrast to muscle stimulation one can usually find a region of poor motion for the electrode-nerve connection.*
- *The electrode has a high stability against low D.C current.*
- *Due to the special design of our electrode, there is little connective tissue reaction around the electrode.*
- *The electrode can be disconnected without any nerve damage by pulling the electrode lead.*
- *Due to the inhomogeneity of the electric flux lines in the nerve, good gain characteristics can be achieved.*

The low rate of clinical complication, i.e., no corrosion, one failure of electrodes during an observation period of 44 patient years, and no significant loss of nerve fibers seems to be related to the high redundancy provided by multiple electrodes on each nerve and a minimal area of contact between nerve and biomaterials (1 mm).

Acknowledgements: We are grateful for the continuous financial support and cooperation of the Austrian Research Foundations FWF and FFF, the Ministry of Research and Science, and the Austria National Bank and the Cardiac Center of the Tajoura Hospital Libya.

REFERENCES

1. Glenn,W.L., W.G.Holcomb, J.B.L.Gee and R.Rath, (1970), Central hypoventilation, long-term ventilatory assistance by radio-frequency electrophrenic respiration, Ann Surg. 172:755-773

2. Marsolais,E.B. and R.Kobetic, (1986), Implantation techniques and experience with percutaneous intramuscular electrodes in the lower extremities. Rehabilitation R & D, 23/3:1-8

3. Donaldson,P.E.K., (1983), The cooper cable: An implantable multiconductor cable for neurological prostheses. Med. & Biol. Eng. & Comp. 21:371-374

4. Thoma,H., (1975), Verfahren und Vorrichtung zur Langzeitstimulation von Nerven und Muskeln, OSPS 330342

5. Thoma H., M.Frey, J.Holle, U.Losert, D.Rosenkranz and H.Stohr, (1981), Experiments on the electrode nerve connection. in Advances in External control of Human Extremities VII, Dubrovnik,pp. 223-237

6. Rosenkranz,D., G.Fenzl, J.Holle, W.Lack, U.Losert, H.Thoma and W.Lipp, (1986), Influence of long-term low direct current on rat ischiadic nerves. Applied Neurophysiology 49:42-52

7. Thoma,H., H.Gerner, J.Holle, P.Kluger, W.Mayr, B.Meister, G.Schwanda and H.Stöhr, (1987), The phrenic pacemaker, substitution of paralyzed functions in tetraplegia. Artificial Organs 10:472-479

8. Burke,R.E., D.N.Levine, P.Tsairis and F.E.Zajac, (1973), Physiological types and histochemical profiles in motor units of the cat gastrocnemius. Physiol. 234:723-748

9. Thoma H., M.Frey, J.Hole, H.Kern, W.Mayr, G.Schwanda and H.Stöhr, (1987), Functional neurostimulation to substitute locomotion in paraplegia patients, **Artificial Organs**, in Andrade J.D. (ed), VCH Publishers, Inc. pp. 515-529

Acknowledgements: We are grateful for the continuous financial support and cooperation of the Austrian Research Foundations FWF and FFF, the Ministry of Research and Science, and the Austria National Bank and the Cardiac Center of the Tajoura Hospital Libya.

REFERENCES

1. Glenn,W.L., W.G.Holcomb, J.B.L.Gee and R.Rath, (1970), Central hypoventilation, long-term ventilatory assistance by radio-frequency electrophrenic respiration, Ann Surg. 172:755-773

2. Marsolais,E.B. and R.Kobetic, (1986), Implantation techniques and experience with percutaneous intramuscular electrodes in the lower extremities. Rehabilitation R & D, 23/3:1-8

3. Donaldson,P.E.K., (1983), The cooper cable: An implantable multiconductor cable for neurological prostheses. Med. & Biol. Eng. & Comp. 21:371-374

4. Thoma,H., (1975), Verfahren und Vorrichtung zur Langzeitstimulation von Nerven und Muskeln, OSPS 330342

5. Thoma H., M.Frey, J.Holle, U.Losert, D.Rosenkranz and H.Stohr, (1981), Experiments on the electrode nerve connection. in Advances in External control of Human Extremities VII, Dubrovnik,pp. 223-237

6. Rosenkranz,D., G.Fenzl, J.Holle, W.Lack, U.Losert, H.Thoma and W.Lipp, (1986), Influence of long-term low direct current on rat ischiadic nerves. Applied Neurophysiology 49:42-52

7. Thoma,H., H.Gerner, J.Holle, P.Kluger, W.Mayr, B.Meister, G.Schwanda and H.Stöhr, (1987), The phrenic pacemaker, substitution of paralyzed functions in tetraplegia. Artificial Organs 10:472-479

8. Burke,R.E., D.N.Levine, P.Tsairis and F.E.Zajac, (1973), Physiological types and histochemical profiles in motor units of the cat gastrocnemius. Physiol. 234:723-748

9. Thoma H., M.Frey, J.Hole, H.Kern, W.Mayr, G.Schwanda and H.Stöhr, (1987), Functional neurostimulation to substitute locomotion in paraplegia patients, **Artificial Organs**, in Andrade J.D. (ed), VCH Publishers, Inc. pp. 515-529