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Use of tripolar electrodes for minimization of current spread in uncut peripheral nerve stimulation

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ABSTRACT

The electrical stimulation of an uncut peripheral nerve requires a countermeasure to avoid the spread of current through a loop pathway formed outside the electrode array. Here the use of tripolar electrodes (TE) is proposed. By binding the two end poles, current spread through the loop pathway can theoretically be eliminated since both end poles are held equipotential. Experimentally, we tested the validity of this approach. In chloralose–urethane anesthetized rats, the left cervical vagus (LCV) was placed on TE which could function as such or as bipolar electrodes (BE) by the use of a selector switch. The spread of current to the adjacent tissues (rectus capitis muscle underlying the LCV, and the right cervical vagus (RCV) incised and translocated beside the target, LCV) was compared between TE and BE. When the stimulus intensity was increased, contraction occurred in the capitis muscle with BE, but not TE. Compound spike potentials of A fiber origin were evoked in the non-target RCV on high-intensity stimulation with BE, but not TE. Constant voltage stimulation of the LCV with TE produced bradycardia of the same magnitude as that with BE. In conclusion, constant voltage stimulation using TE can minimize current spread without changing the stimulus's effects.

1. Introduction

On the electrical stimulation of a cut end of a peripheral nerve, the excitation of the nerve placed on the stimulating electrodes is caused by the longitudinal current that comes from the anodal pole, penetrates the membrane of an axon (causing hyperpolarization), passes longitudinally through the axoplasma, and flows outward toward a cathode pole (causing depolarization, then excitation, Fig. 1Aa). In uncut nerves, however, a loop current pathway is additionally formed which includes the target nerve, and the adjoining non-target tissues attached to both limbs of the target nerve (Fig. 1Ab). Current can spread from the anodal pole through one limb of the target nerve to non-target tissues and from there through the other limb back to the cathodal pole, causing undesired effects especially when the tissues are excitable.

Tripolar electrodes, often employed for stimulating an uncut nerve enclosed in a cuff, are widely used clinically to steer a stimulus current in terms of direction or targeting. Modifications of tripolar or multipolar electrodes have allowed investigators to selectively activate specific nerve bundles (Grill and Mortimer, 1996; Sweeney et al., 1990; Veraart et al., 1993), or specific nerve fiber groups (Accornero et al., 1977; Rijkhoff et al., 1997; van den Honert and Mortimer, 1979) and to control the direction of action potential conduction (van den Honert and Mortimer, 1981). It should be emphasized that tripolar electrodes can in principle confine current flow within the cuff (Accornero et al., 1977; Sweeney et al., 1990; van den Honert and Mortimer, 1981). However, this feature has rarely been used to prevent the spread of current in nerve stimulation experiments. In the present study, we established an experimental setup with which current spread and stimulation efficacy could be compared between stimulation with tripolar electrodes and that with conventional bipolar electrodes. First, both end poles of tripolar electrodes were bound together and connected to a cathodal output, and the central pole was connected to the anodal output of a stimulating isolator (Fig. 1Ac). Second, a constant voltage was employed instead of a constant current to maintain an effective longitudinal current flow (from J1 to J2 in Fig. 1) unchanged irrespective of the electrode arrangement as long as the interpolar resistance remained the same. Stimulation with the tripolar electrodes should be as effective as that with bipolar electrodes in depolarizing the target nerve, but should prevent the spread of current to the surrounding non-target tissues because loop current flow is theoretically suppressed owing to equipotentiality between the cathodal end poles.

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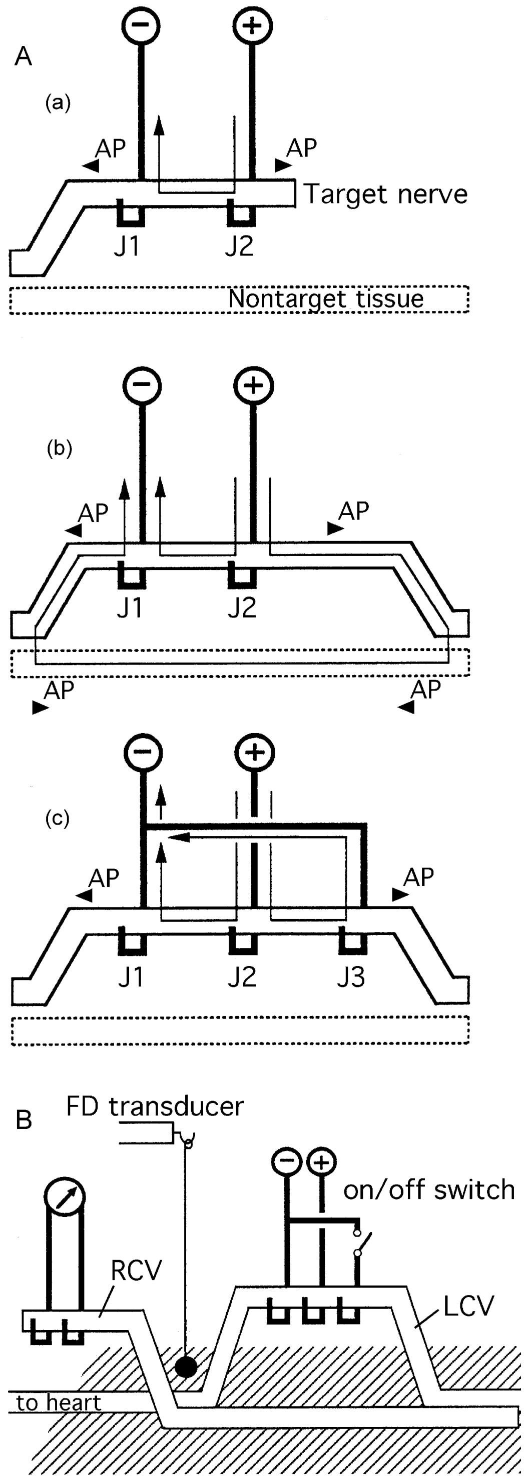

Fig. 1. Pathways of current flow on peripheral nerve stimulation (A) and the experimental setting (B). (A) Panel (a) shows current flow on conventional stimulation using bipolar electrodes (BE) of an end of a cut nerve. Panel (b) shows the formation of an additional flow of current round a loop pathway when an uncut nerve is stimulated with BE. Note that electrical stimulation inevitably generates a voltage difference between J1 and J2 causing current to flow round the loop in addition to passing directly through it. Panel (c) shows current flow on electrical stimulation with end-pole bound, tripolar electrodes (TE). This electrode configuration keeps points J1 and J3 equipotential so that no current flows from J3 to J1 through the loop pathway. Arrowheads indicate the occurrence and direction of evoked physiological action potentials (AP). In both the situation of TE and BE stimulation, AP will travel through the nerve along both directions in response to stimulation (a–c), causing a physiological effector response of the activated nerve. However, the large stimulation current spreading through the loop circuit will be absent when stimulating in the tripolar configuration (c). (B) Experimental setting for comparing effects caused by current spread on stimulation of the left cervical vagus nerve (LCV, target nerve) with different electrodes. Use of an on/off switch allows comparison of the respective effects produced by stimulation with BE and TE. Compound spike potentials in the non-target, right cervical vagus nerve (RCV), and muscle contraction in the rectus capitis muscle evoked by current spread were picked up through recording electrodes and the FD transducer, respectively.

2. Materials and methods

2.1. General procedures

Eleven male Wistar rats, 300–400 g in body weight, were anesthetized with intraperitoneal injections of α-chloralose (60 mg/kg) and urethane (600 mg/kg). Polyethylene tubes were introduced into the left femoral artery and vein for the subsequent recording of blood pressure and administration of drugs, respectively. The trachea was cannulated and animals were artificially ventilated following immobilization with an intravenous injection of succinylcholine (10 mg/kg). The stability of blood pressure and heart rate was taken as an index for maintaining the adequate depth of anesthesia under paralysis. This study was a terminal experiment, and rats were sacrificed by administration of an excessive dose of α-chloralose and urethane at the end of the experiment. The study was approved in advanced by the Ethics Committee of Mie University.

2.2. Electrodes used for stimulation

Experiments were performed in an '*in situ* moist chamber' using air-exposed electrodes, on which the target, the left cervical vagus nerve, detached from the adjacent tissues, was placed. The nerve together with the electrodes was covered untouched with a wet cotton sheet in order to keep the air inside moist throughout. In this condition, air served a similar role to mineral oil, fluorocarbon or an insulation cuff. The electrodes had three poles, each interpolar distance being 1.25 mm. The central pole of the electrodes was connected to the anodal output of an insulator. An on/off switch was interposed in the lead wire connecting the two end poles. Turning this switch on and off allowed a precise comparison of the effects of the tripolar and bipolar electrode modes of stimulation. Thus, the electrodes could act either as tripolar electrodes with a central anodal pole and two cathodal end poles bound when the switch is on, or as bipolar electrodes when the switch is off. The order of the different stimulation methods (bipolar and tripolar) was random, and effects of the stimulation mode were confirmed at least several times by alternate stimulation. The electrical stimulation was 0.5 ms in width, 2, 5, 10, 15, 20, 30 V in intensity, and 1 Hz in frequency unless indicated otherwise.

2.3. Nerve stimulation

The skin covering the ventral neck region was incised and the sternocleidomastoid, sternohyoid, and omohyoid muscles were removed in succession. The cervical vagus of the left side was detached from the surrounding tissues and the middle portion was gently raised and placed on the tripolar electrodes. The vagus nerve was cut at the carotid bifurcation so it could be placed on the electrodes without excessive stretching. The peripheral portion and the cut end of the vagus nerve were intentionally attached to the ventral surface of the rectus capitis muscle. In this condition, the vagus nerve, though cut, would behave like an uncut nerve in terms of current spread. Tripolar electrodes with the middle portion of the vagus nerve were hung in moist air separated from the rectus capitis muscle (Fig. 1B). The length of the nerve suspended in air was 1 mm for each side.