Communications

Simultaneous Polarographic and Electrophysiological *In Vivo* Measurements Through Optoelectronic Interconnection

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Abstract—**It is shown that simultaneous pickup of polarographic and electrophysiological signals, which is usually prevented by a severe electrical interference, becomes possible when the polarograph is connected to its electrodes via an optoelectronic link. The sources of interference in simultaneous measurements are discussed, as well as the advantage of breaking the ground loop. Reported experimental data show that the simultaneous signals have the same quality as if separately detected.**

I. INTRODUCTION

In physiology, simultaneous *in vivo* recording of concentrations of chemical species by polarography [1] and biological electrical signals by electrometry (such as unitary neuronal activity, electroencephalography, and electromyography) [2] is a very attractive method because it allows to correlate the concentration of a substance in a body district with the monitoring of its effect in real time.

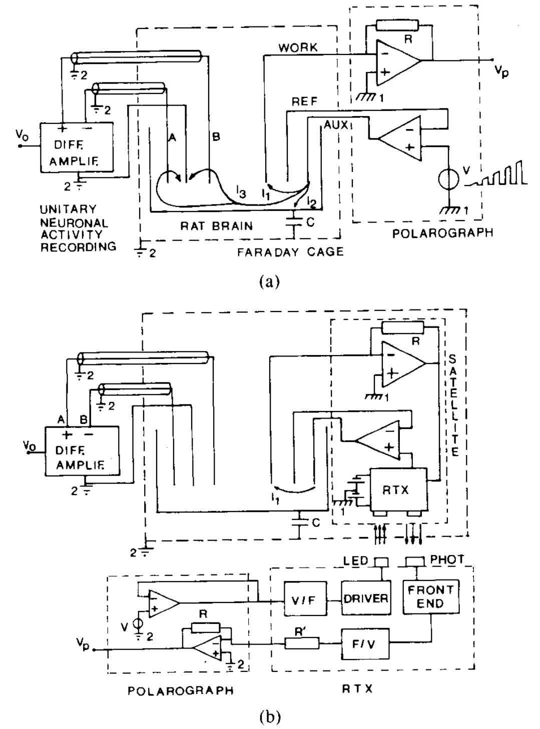
Unfortunately, when the two systems are operating in proximity, a strong electrical interference is generated on the electrophysiological signal because of the relatively large excitation current of the polarograph which flows through the common return (ground) path. Even with a careful wiring and guard-electrode layout, the simultaneous measurement is rarely better than erratic and cannot be used routinely.

By using an optoelectronic transceiver directly mounted onto the polarographic electrodes, so that the ground loop is suppressed, the electrical interference becomes negligible and both electrophysiological and polarographic signals are of the same quality as if separately detected.

In the following, we specifically consider simultaneous brain polarography and unitary neuronal activity monitoring [2]–[4]. This application is important, for example, as a research tool to clarify the mechanism of action of several drugs since it allows to correlate the extracellular concentration of brain neurotransmitters and their metabolites with the electrical neuronal activity. Because of the comparable amplitudes and the similar electrode arrangement, the proposed method can be applied to the detection of other low-level biological signals concurrently to polarography, e.g., in electroencephalography and electromyography [2].

II. ANALYSIS OF THE MEASUREMENT SETUP

A fairly general measurement scheme is shown in Fig. 1(a). The polarographic electrodes are connected as in the standard differential pulse polarography [1]. Voltage pulses of increasing amplitude (or pulses of constant amplitude superimposed to a voltage ramp) are applied by the driver circuit between the reference electrode and the working electrode.



(a)

(b)

Fig. 1. Simultaneous polarographic and electrophysiological measurement scheme: (a) wiring interconnection and (b) optoelectronic interconnection.

The oxidation current I_1, carrying the information on the concentration of chemical species in solution, is read by a precision current amplifier. The polarograph has a fully differential structure and its own ground (marked "1" in Fig. 1).

The electrophysiological signal, i.e., the voltage difference between electrodes A and B, is read by a differential high-impedance amplifier. The third electrode is the zero-potential reference and is connected to a separate ground (marked "2" in Fig. 1). A Faraday cage can be used to shield the electrophysiology circuits from electromagnetic interference induced by laboratory instruments and ac power lines, and it is also connected to ground "2."

In a standard wiring layout, the two grounds "1" and "2" shall somewhere be connected together. Then, three current components are sunk from the auxiliary electrode, i.e.: i) the *oxidation current* I_1; ii) a *parasitic capacitive current* I_2 flowing through the body of the animal and the distributed capacitance C to the Faraday cage; and iii) a *parasitic conductive current* I_3 (both ac and dc components) flowing through the brain to the electrophysiology ground electrode.

Current I_3 flowing through the animal brain produces a voltage unbalance at the electrodes A and B, whose actual amplitude depends on the electrode geometry, but is always at least an order of magnitude larger than the electrophysiological signal. A guard-

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electrode return for the ground of the electrophysiological signal (not shown in Fig. 1) could only attenuate the interference. Indeed, typical values of polarographic pulses are in the range −200 to +400 mV with repetition period of about 50 ms to be compared to unitary neuronal activity signals ranging from 10 to 100 μV with repetition period 10 ÷ 100 ms; thus, decoupling factors of the disturbances of at least 50 dB would be required to attain an adequate S/N ratio and to minimize artifacts. Typical waveforms obtained with a careful placing of electrodes are shown for illustration in Fig. 2(a) and in Fig. 3(a).

An additional reason for minimizing current I_3 is the damage due to its dc component on the tissue near the auxiliary electrode (which has a typical current capability in excess of 10 mA), with a corresponding reduction of the useful lifetime of this electrode.

Several approaches have been proposed to tackle such interference. The simplest one consists in switching both electrode systems [3], so that the low-level signal is monitored only during the dead intervals between two polarographic measurements, typically every 2 min. Obviously, in this way several features of the electrophysiological signal are lost.

Alternatively, the separation of the ground connections of the polarographic and electrophysiological systems, by floating one of the two grounds, would eliminate the dc component of I_3 and greatly reduce its ac component, thus avoiding tissue damage and reducing spike artifacts. However, electromagnetic interference from laboratory instrumentation and power lines is now increased since the potentials of the two grounds fluctuate with respect to each other. Consequently, a voltage disturbance arises on the auxiliary electrode with respect to the electrophysiological ground and an ac current is forced through the parasitic distributed capacitance between the two grounds. Unless the laboratory environment is electromagnetically very quiet, this disturbance can be even greater than that due to crosstalk. An improvement is obtained when the auxiliary electrode is connected to the Faraday cage [4] so that essentially no current flows between them. Yet, a small current is drawn from the working electrode (as limited by the feedback resistance $R \approx 1\ \mathrm{M\Omega}$). As a result, the typical S/N ratio is not better than a few units [4].

III. The Optoelectronic Interconnection

The schematic of the optoelectronic interconnection for the polarograph is shown in Fig. 1(b). The optoelectronic transceiver, described in detail in a previous paper [5], consists of a fixed unit connected to the polarograph and a miniaturized satellite unit mounted on the animal and connected to the electrodes. The two-way transmission channel relies on infrared radiation reflected and diffused from the laboratory walls and ceiling, and allows an operating range of several meters. LED's and photodiodes are used as emitters and receivers on both satellite and fixed units. Frequency modulation of the electrical subcarriers is used to ensure an adequate S/N ratio and intrinsic amplitude calibration.

The optoelectronic system is basically a wireless interconnection between the laboratory animal and the polarograph. The satellite circuit is all contained in the Faraday cage with the electrode connections, and no wire of the polarographic system goes through the Faraday cage. In this way, environmental electromagnetic interference is virtually eliminated.

In addition, as the satellite unit is battery operated, the grounds of the polarographic and electrophysiological measuring systems are completely separated and both conductive and capacitive currents I_2 and I_3 become negligible.

IV. Experimental Results

Using the standard wiring interconnection, typical recordings of unitary neuronal activity in simultaneous measurements are obtained as shown in Fig. 2(a). The useful signal is the nonperiodic spike comb marked "1," while the larger periodic pulses (marked "2") are the artifacts generated by the polarographic system synchronously with the driving waveform. In the same conditions, the optoelectronic transceiver gives the result shown in Fig. 2(b). The S/N ratio is now the same as with a standard separate determination since all artifacts have been suppressed and the commonly employed digital processing of the waveform can be easily carried out [6].

Another example of simultaneous measurement performed on a low-level electrophysiological signal, for which the analog details of the waveform are important, is electroencephalography [6]. The recording obtained with the wiring connection [Fig. 3(a)] shows that during the polarographic determintion the low-level EEG signal is completely corrupted by interference. On the other hand, with the optoelectronic transceiver the encephalogram is completely unaffected as shown in Fig. 3(b).

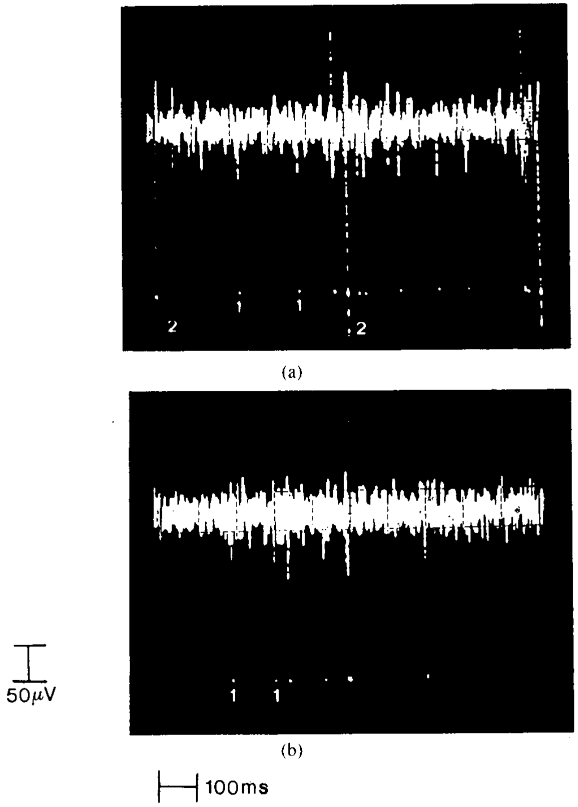

Fig. 2. Action potential of a single neuron as detected in a simultaneous polarographic measurement [1) signal spikes; 2) artifacts due to polarography]: (a) wiring interconnection and (b) optoelectronic interconnection.

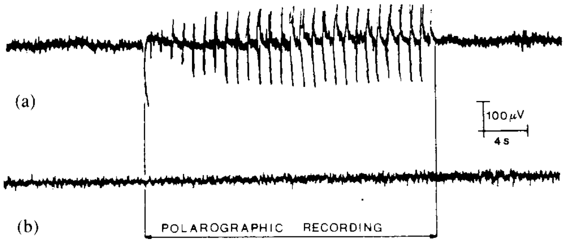

Fig. 3. Electroencephalographic recording as obtained in a simultaneous polarographic measurement: (a) wiring interconnection and (b) optoelectronic interconnection.

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Design and Calibration of a High-Frequency Oscillatory Ventilator

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Abstract—**High-frequency ventilation (HFV) is a modality of mechanical ventilation which presents difficult technical demands to the clinical or laboratory investigator. The essential features of an ideal HFV system are described, including wide frequency range, control of tidal volume and mean airway pressure, minimal dead space, and high effective internal impedance. The design and performance of a high-frequency oscillatory ventilation system is described which approaches these requirements. The ventilator utilizes a linear motor regulated by a closed loop controller and driving a novel frictionless double-diaphragm piston pump. Finally, the ventilator performance is tested using the impedance model of Venegas [1].**

INTRODUCTION

High-frequency ventilation (HFV) is a relatively new form of mechanical ventilation which operates at supranormal (1-30 Hz) frequencies (f) while using tidal volumes (V_t) equal to or smaller than the anatomic dead space. The ability of these systems to adequately oxygenate and ventilate both humans and experimental animals is well documented [2]-[4]. A large variety of HFV systems have been used [1], [5]-[7], and, while each has its advantages and disadvantages, it is clear that an ideal system should have certain characteristics. These features include wide frequency range, easily controlled and reproducible tidal volume, minimum equipment dead space, independently controlled mean airway pressure or lung volume, and variable inspiratory : expiratory time ratio. The ventilator should also have an effective high "internal impedance," as described by Venegas [1], so that its output is relatively insensitive to changes in respiratory system impedance.

In this communication we describe a high-frequency oscillatory ventilator which approaches the above requirements. It uses a linear motor regulated by a second-order closed-loop controller and driving a novel frictionless double-diaphragm piston-cylinder pump. Mean airway pressure is controlled by a servo-control valve on the bias flow outlet, and tidal volume is measured by an in-line pneumotachograph. The design and implementation of this system are described emphasizing the application of general engineering techniques and principles, and the ventilator performance is tested using the impedance model of Venegas [1].

GENERAL DESCRIPTION

The high frequency ventilation system used is schematically pictured in Fig. 1. It is a bias-flow oscillator system, with regulation of mean airway pressure ($\bar{P}_{aw}$) by a servo-control valve on the vacuum line. The ventilator itself consists of a linear "voice coil" motor (Infomag model 15) driven by a second-order closed-loop controller (see below). The motor drives a lightweight hollow aluminum piston which is sealed to the Plexiglas cylinder with back to back rolling diaphragms (Bellofram Corp., Burlington, MA); there are no friction seals. With a piston cross-sectional area of 45 cm^2 this system is able to deliver tidal volumes over 50 mL at 25 Hz and up to 100 mL at frequencies below 5 Hz. Other advantages of this design include the elimination of piston dead space at all tidal volumes, continuously variable frequency and tidal volumes, minimization of piston-cylinder alignment problems, and the ability to follow arbitrary input waveforms.

HFV was delivered through a 23-cm-long 2.5-cm-diameter straight Plexiglas tube which was connected to the endotracheal tube via a tapered rubber connector. $\bar{P}_{aw}$ was measured via a small flush sidearm at the center of this conduit with a Validyne DP45 transducer (±140 cm H_2O). This arrangement has been shown to minimize the errors associated with airway pressure measurement during HFV [8]. The fresh air bias flow entered through a small opening at the dog end and exited through another at the piston end of the plexiglas tube. A bias flow rate of 8 L/min, measured with a Matheson Mass Flowmeter (Model 8160, Matheson Co., E. Rutherford, NJ), was used in all experiments. The pressure transducer signal was amplified and filtered with a Validyne CD100-3 carrier amplifier and used as the input to a Brown Electrodynamics servo amplifier, which controlled a valve between the bias flow exhaust and a vacuum source to regulate $\bar{P}_{aw}$. This simple linear feedback $\bar{P}_{aw}$ controller was empirically adjusted to be slightly underdamped, so that $\bar{P}_{aw}$ was restored smoothly within 3-4 s after a step change in the input or a transient disturbance.

MECHANICAL SPECIFICATIONS

A. Linear Motor

This type of motor consists of a permanent toroidal magnet and a cylindrical coil which moves freely along its axis. Current running through the coil causes it to exert a proportional force along the axis of the magnet. An Infomag model 15 linear motor was used which has a force constant of 2.9 lb/amp, a constant force stroke of 5 cm (total stroke 9.1 cm), and a maximum power dissipation (air cooled) of 280 W. The coil was mounted on a 3/8 in aluminum shaft and was supported on two linear ball bearing bushings which were press fit into the 5/8 in axial bore of the motor housing; no

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