Available online at www.sciencedirect.com
ScienceDirect
Medical Engineering & Physics 30 (2008) 550–562
Medical Engineering & Physics
www.elsevier.com/locate/medengphy

Tripolar-cuff deviation from ideal model: Assessment by bioelectric field simulations and saline-bath experiments

Iasonas F. Triantis [a], Andreas Demosthenous [b,*]

[a] Institute of Biomedical Engineering, Imperial College, London, London SW7 2AZ, UK
[b] Department of Electronic and Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, UK

Received 14 February 2006; received in revised form 28 May 2007; accepted 12 June 2007

Abstract

Ideally, interference in neural measurements due to signals from nearby muscles can be completely eliminated with the use of tripolar cuffs, in combination with appropriate amplifier configurations, such as the quasi-tripole (QT) and the true-tripole (TT). The operation of these amplifiers, is based on the theoretical property of the nerve cuff to produce a linear relationship of potential versus distance along its length, internally, when external potentials appear between its ends. Thus, in principle, electroneurogram (ENG) recordings from an ideal tripolar cuff would be free from electromyogram (EMG) interference generated by nearby muscles. However, in practice the cuff exhibits non-ideal behaviour leading to “cuff imbalance”. The main focus of this paper is to investigate the causes of cuff imbalance, to demonstrate that it should be incorporated as a main parameter in the theoretical ENG-recording cuff electrode model. In addition to cuff asymmetry and tissue growth, the proximity of the interference source to the cuff is shown to result in cuff imbalance. The influence of proximity imbalance on the performance of the QT and TT amplifiers is also considered. Proximity imbalance is studied using bioelectric field simulations and saline-bath experiments. Variation is observed with both distance (40 mm and 70 mm was examined) and orientation (0–180°), with the latter causing a more severe effect especially when the source dipole and the cuff are vertical to each other. The simulations and measurements are in close agreement. Tissue growth imbalance and asymmetry imbalance are also investigated in vitro. Finally, the signal-to-interference ratio (SIR; ENG/EMG) of the QT and TT amplifiers is examined in the presence of cuff imbalance. It is shown that proximity imbalance results in their SIR to peak only at certain cuff orientation values. This important finding offers an insight as to why in practice ENG recordings using these amplifiers have been widely reported to be degraded by EMG interference.

Keywords: Tripolar cuff; Nerve cuff; Cuff electrodes; Cuff imbalance; ENG; EMG; Signal-to-interference ratio (SIR); Quasi-tripole; True-tripole; Screened-tripole

1. Introduction

The cuff electrode has been established as a neural interface that can be used both for neural recording and stimulation [1–13]. It is non-invasive to the nerve and suitable for chronic implantation [2]. Typical cuffs consist of insulating tubes, consisting of biocompatible flexible insulating materials such as silicone rubber or polyamide [14], with ring electrodes made of platinum-iridium or stainless steel attached to the inside wall, covering most of the circumference (Fig. 1). A longitudinal slit is left along the tube so that the cuff may be placed around the nerve, where after the split is usually glued or covered by a flap [7].

Recording electroneurograms (ENG) using cuff electrodes was shown in [15] to increase signal amplitude due to the local restriction of the extracellular space. Extracellular ion currents create potential differences inside the cuff as the action potential moves across its length, which can be measured by the ring electrodes placed inside it. Cuff-recorded ENG can be used for applications including chronic studies of physiology and pathology of the neuromuscular system, studies of the regeneration of axotomised nerve fibres and the status of the nerves after damage and for feedback in functional electrical stimulation (FES) based neuroprosthetic devices [10]. FES is used for partial restoration after

* Corresponding author.
E-mail address: a.demosthenous@ee.ucl.ac.uk (A. Demosthenous).

1350-4533/$ – see front matter © 2007 IPEM. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.medengphy.2007.06.002

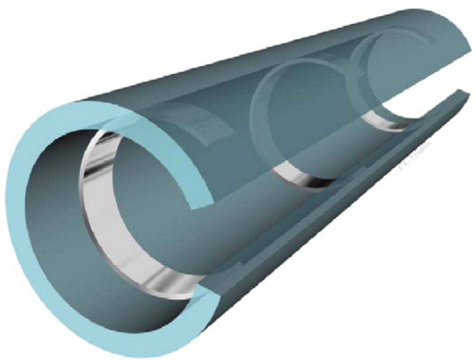

Fig. 1. Typical tripolar-cuff electrode (slit uncovered).

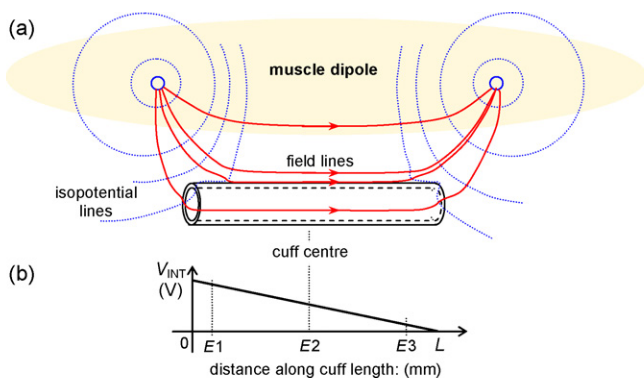

Fig. 2. (a) The perturbation of the muscle dipole field by the cuff, similar to the effects described in [10]. (b) The cuff linearizes the EMG field (V_{INT}) inside it [17]. L is the cuff length and E1, E2 and E3 are the positions of the three cuff electrodes.

spinal cord injury offering assistance in applications such as foot-drop, hand grasp in tetraplegics, and bladder voiding [11–13,16]. However, the presence of interference from sources outside the cuff, such as electromyogram (EMG) from nearby muscles and stimulus artefact when stimulation is applied, degrades the ENG recordings [7–10,16].

Interference signals cause ionic currents to flow through the tissue inside the cuff. The muscle's field lines and the respective isopotential lines are distorted by the cuff (Fig. 2a). As the medium inside the cuff is only resistive, there are no significant phase variations to the interfering potentials across the electrodes and ideally the potential varies linearly with distance across the length of the cuff (Fig. 2b) [16,17].

In general, the frequency range of naturally occurring ENG signals recorded using cuffs, is 500 Hz to 10 kHz with amplitudes of the order of a few μV. Myoelectric (EMG) potential amplitudes are around 1 mV pk–pk, with a frequency range of 1 Hz to 3 kHz [4,5,15]. Therefore, the spectra of the two signals overlap and although the ENG signal power concentrates mainly around 800 Hz and 2 kHz, while the EMG peaks between 100 and 250 Hz, EMG greatly degrades ENG measurements, because it can be up to three orders of magnitude larger [8–12,16]. A measure of EMG contamination of ENG measurements is the ENG-to-EMG ratio, as used in [8,16,18]. In this paper this ratio is expressed as the signal-to-interference ratio (SIR), used for expressing the signal quality both at the input and at the output of amplifier configurations used with cuff electrodes.

Ideally, EMG interference in neural measurements can be completely eliminated with the use of tripolar cuffs, in combination with appropriate amplifier configurations such as the quasi-tripole (QT) and the true-tripole (TT) [6–8,16]. As reported in [6–8,16], in both systems interference rejection is based on the ability of the cuff to linearize the internal potential field generated by external sources [4]. However, it has been widely reported [2–11,19–23] that EMG contaminates ENG measurements, even when tripolar-cuff amplifiers are used. This means that the real cuff differs from the ideal model, which is the basis of the design of the QT and the TT. This effect, which causes the presence of interference at the output of tripolar-cuff amplifiers, is termed "cuff imbalance" [8,16,24]. This paper examines the factors that cause the cuff to deviate from the ideal model, thus offering insight as to why tripolar-cuff ENG amplifiers (i.e., QT and TT, see Fig. 3) fail to eliminate EMG breakthrough. The work described here is a development of [25] and provides new results and further insights into cuff imbalance. The study was conducted using bioelectric field simulations and saline-bath experiments.

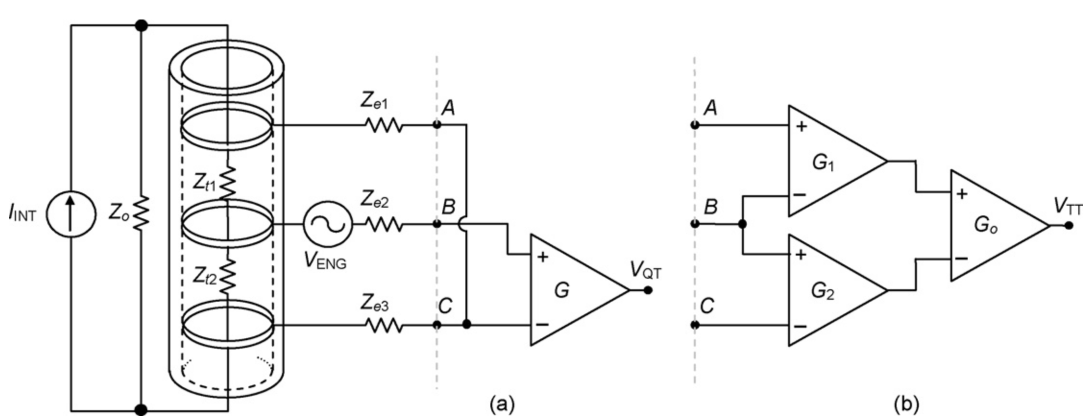

Fig. 3. Tripolar ENG amplifier configurations; (a) the QT connected to a tripolar cuff (cuff lumped model is shown), (b) the TT. V_{ENG} is the ENG source. Nodes A, B and C are circuit nodes. Typical impedance values: $Z_{\mathrm{o}} = 200\,\Omega$, $Z_{\mathrm{t}} = 2.5\,\mathrm{k}\Omega$, $Z_{\mathrm{e}} = 1\,\mathrm{k}\Omega$, $I_{\mathrm{EMG}} = 1\,\mu\mathrm{A}$, $V_{\mathrm{ENG}} = 3\,\mu\mathrm{V}$ [26].