Bioelectric field simulations for studying cuff-electrode interface errors in peripheral nerve signal recordings

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Abstract— Ideally, interference in neural measurements due to signals from nearby muscles can be completely eliminated with the use of tripolar nerve cuff electrodes, in combination with appropriate amplifier schemes. In practice the cuff departs from its ideal model leading to *cuff imbalance*. As a result, the output nerve signal of such amplifiers has been widely reported to be degraded by interference, making it difficult to use neural recordings as feedback to stimulators. This paper investigates relationship of cuff – interference-source proximity on cuff imbalance and its influence on the performance of well established amplifier configurations. The study was conducted using bioelectric field simulations.

I. INTRODUCTION

SPINAL cord injury (SCI) leaves parts of the body permanently paralysed. However, unaffected functions of the peripheral nerves can be used as a source of sensory information from parts of the body. The electrical signal due to neural activity is called *electroneurogram* (ENG) and it can be monitored using cuff electrodes or “cuffs” placed around the nerves of interest. The recorded ENG can be used to control stimulation, as in the implant shown in Fig. 1, used for partial rehabilitation of SCI-incurred incontinence [2].

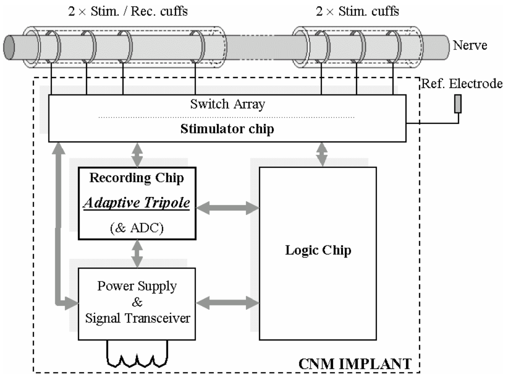

Figure 1. An implant for electroneurogram-triggered stimulation for incontinence rehabilitation.

Monitoring of the μV-order ENG requires amplifier schemes that provide immunity to muscle signal (electromyogram or EMG) interference (several mV) [3]. Ideally, EMG elimination is possible with the use of tripolar cuff electrodes, in conjunction with specific amplifier configurations, namely the "quasi-tripole" (QT) and the "true-tripole" (TT) [1]. However, EMG contamination has been commonly reported even when these tripolar cuff amplifier configurations are used [3]. This problem is attributed to *cuff imbalance* [1].

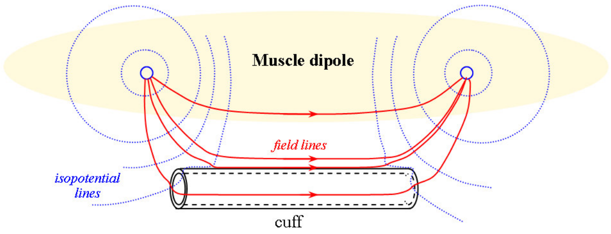

Figure 2. The perturbation of the muscle dipole field by the cuff

II. CUFF IMBALANCE

Cuff electrodes consist of insulating tubes with ring electrodes attached to the inside wall. Figure 3 illustrates a diagram of a tripolar cuff along with external and internal tissue impedances. Ideally its ability to internally "linearize" [3] the potential gradient of the external interference (EMG), caused by I_{INT} flowing through the tissue resistances Z_{t1} and Z_{t2}, results to the diagram under the label "ideal". In that case the EMG components across the two halves of the cuff are equal and anti-phase and can be cancelled by addition. The ENG appears as a source in series with the middle electrode.

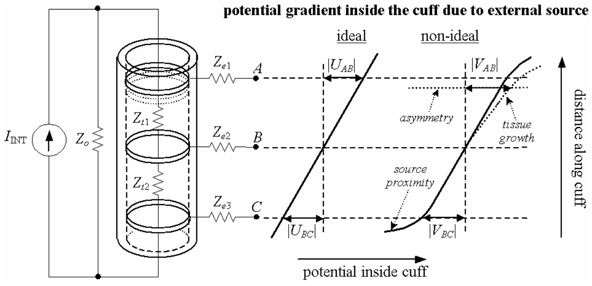

Figure 3. Model of the tripolar cuff with ideal and non-ideal interference potential gradients

In the ideal situation where the tissue impedance inside it is homogeneous, TT and QT will have zero output EMG. In real conditions EMG potential gradient inside the cuff will be similar to the diagram labeled "non-ideal". In the presence of imbalance $|V_{AB}| \neq |V_{CB}|$, these being the EMG components across points *AB* and *CB*, respectively. With reference to Fig. 2, cuff imbalance (X_{imb}) is defined as:

$$X_{\text{imb}} = \left\{ \frac{|V_{AB}| - |V_{CB}|}{|V_{AB}| + |V_{CB}|} \right\} \times 100\% \tag{1}$$

Manuscript received June 30, 2006.

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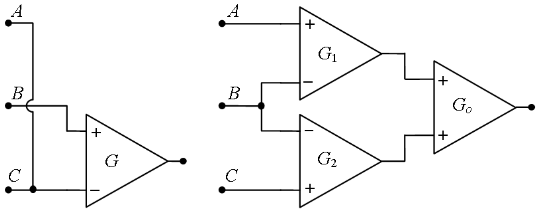
where V_{AB} and V_{CB} are the voltages across electrode points *AB* and *CB*, respectively, caused by the external interference ionic current (I_{INT}) flowing through the tissue resistances Z_{t1} and Z_{t2}.



(a) (b)

Figure 4. Tripolar ENG amplifier configurations; (a) quasi-tripole (QT), (b) true-tripole (TT) [1]

A solution to cuff imbalance has developed by the authors and described in [1]. The "adaptive tripole" (AT – Fig. 5), featuring an analogue automatic gain control configuration based on the TT, offers adaptive cuff imbalance correction using a frequency independent method, thus reducing the interference and at the same time retaining neural information throughout the bandwidth of interest. An IC version of the AT has been developed, making the system implantable [4].

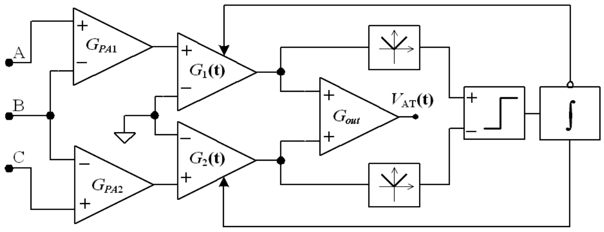


Figure 5. The adaptive-tripole (AT) block diagram; Feedback-controlled variable gain stage provides cuff-imbalance correction [1]

The major cause of cuff imbalance is inhomogeneous tissue re-growth after implantation [2] and Figure 3 shows how it affects the potential gradient of EMG inside the cuff. An additional cause is cuff asymmetry due to imperfect electrode placement, but this can almost be eliminated with novel cuff fabrication techniques [5]. The effect of tissue re-growth is not possible to control but fortunately it is a very slow varying error [6]. These sources of error can be corrected by the AT but do not require the control stage to be on continuously. This can reduce the power consumption of the implant, with the control stage turning on occasionally (after tissue growth has stabilized). However, in-vivo experiments performed with the AT have indicated that cuff imbalance can be affected by the position of the interference source relative to the recording cuff. In this case the AT would have to be on at all times and would have to be designed to have a short convergence time. In order to understand how the operation of the cuff is affected by its proximity to the surrounding muscles, simulations were performed and are presented in this paper. The results were confirmed by in-vitro experiments presented elsewhere [2].

In a study by Rahal *et al* [7], cuff end-effects were reported to cause *nonlinearity* near the cuff ends. As a follow-up from that work, in this paper we show that these end-effects relate to the *proximity* of the external interference source to the cuff. Hence, cuff imbalance is also caused by cuff end-effects which depend on variations of its orientation and distance relative to the interference source. The results also demonstrate that the interference amplitude inside the cuff also depends on proximity.

III. METHODS

In order to study how the cuff interacts with an external field and how cuff imbalance is affected by proximity, 2-dimensional (2-D) field simulations were performed in Ansoft® Maxwell® software package. This software was chosen because it allows volume conductor simulations with fields in materials like saline which is widely used to simulate biological tissue [8]. A monopole source was used for the interference field in [7], however the muscle source is usually represented by a dipole [9] and that was preferred here.

The cuff model used consisted of the upper and lower walls of the cuff cross-section, placed in a saline plane close to an electric dipole representing the interference field. The distance between the cuff walls (corresponding to the cuff diameter) was 2mm and the cuff length was 20mm. The cuff model, which did not include electrodes, was rotated in different angles relative to the source and field simulations were performed for each angle (Fig. 6). The model material was polyamide. The range of cuff orientation ϕ varied through chosen values from 0° to 180°. The signal amplitude of the dipole was chosen empirically so that the voltage across the cuff was approximately 1mV. The distance d between the interference source and the cuff centre varied, between 4cm and 7cm away from the cuff centre. The dipole orientation was 90° relative to the cuff axis.

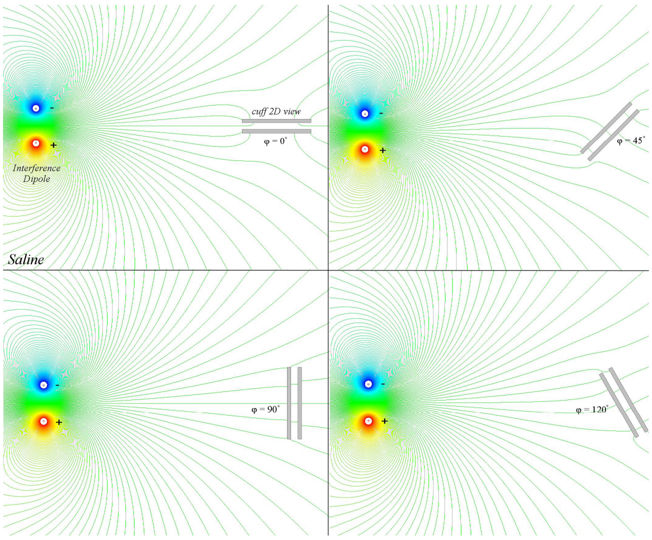


Figure 6. Simulations: Two-dimensional view of cuff cross-section (electrodes excluded). The cuff was placed in a saline plane and an electric dipole represented the muscle. Here, the effect of cuff rotation to the isopotential lines of the dipole is shown for four values of φ.

IV. RESULTS

The effect of cuff rotation to the isopotential lines of the dipole is illustrated in the four different cases shown in Fig. 6, which correspond to $\varphi = 0°$, 45°, 90° and 120°. In the first case ($\varphi = 0°$), the cuff is shown to perturb the isopotential lines caused by the interference dipole, although no variation is evident inside it. For the next three cases displayed in this figure, the isopotential lines become mostly linear and parallel ones inside it, indicating linear variation of potential. The effect seems to be more symmetrical in the $\varphi = 90°$ case. The difference in the distance between the internal field lines in the last three cases suggests a slight variation of the potential slope inside it, especially close to the edges.

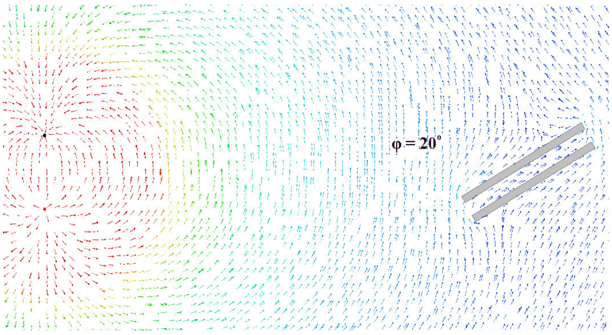


Figure 7. Electric field lines for φ = 20°

The electric field lines and, in effect, the ionic current paths are illustrated in Fig. 7 for $\varphi = 20°$. The arrows follow almost a straight-line course inside the cuff, with the slope of the current path approximately parallel to the cuff walls. The current path becomes curved close to the edges, due to the end-effects.

Based on the plots above, the interference potential gradients inside the cuff, for 6 values of φ (0°, 30°, 45°, 60°, 90°, 135°), were plotted along the cuff wall, for dipole-cuff distances of 4cm and 7cm (Figs 8a and b, respectively). The graphs indicate that the potential gradient inside the cuff is mostly linear, as theory suggests, especially if the regions very close to the edges are excluded. The plots were centered on the horizontal axis. The 45° and 135° cases overlapped.

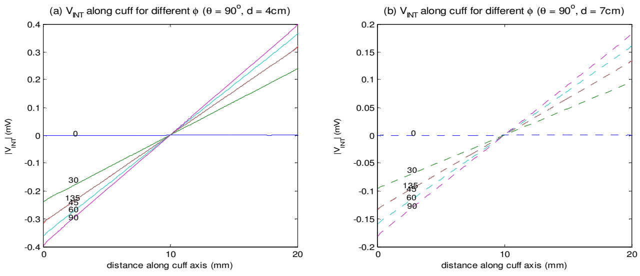


Figure 8. Interference potential gradients inside the cuff along its length

A. *Effect of proximity on imbalance and EMG amplitude*

The amplitude variation of the signal across the cuff as a function of φ is illustrated in Fig. 9a. The potential across the cuff increases as φ varies from 0° to 90° and then drops again. For d = 4cm, the maximum amplitude is in the vicinity of 1mV (0.8mV pk-pk) for 90°. When d increases to 7cm, maximum interference amplitude drops to about half.

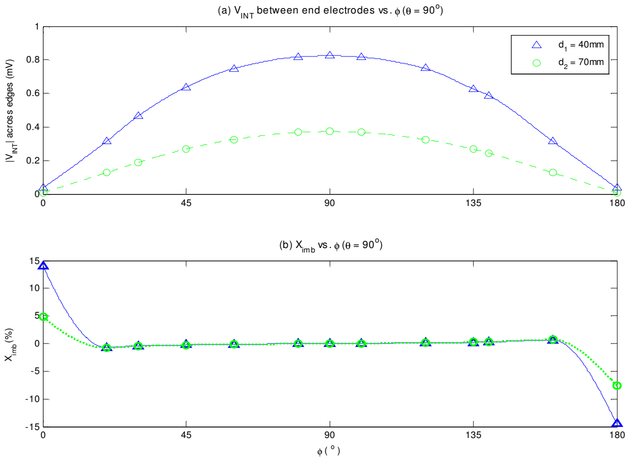


Figure 9. (a) Absolute interference amplitude variation due to cuff orientation change, for d of 4cm and 7cm. (b) Corresponding imbalance variation as cuff orientation varies.

In Fig. 10a, interference potential variation is displayed for virtual electrode positions inside the cuff, with the amplitude dropping as the electrodes are shifted from 2mm to 4mm away from the cuff edges. The variation of the interference potential with cuff orientation in all three cases is similar to Fig. 9a.

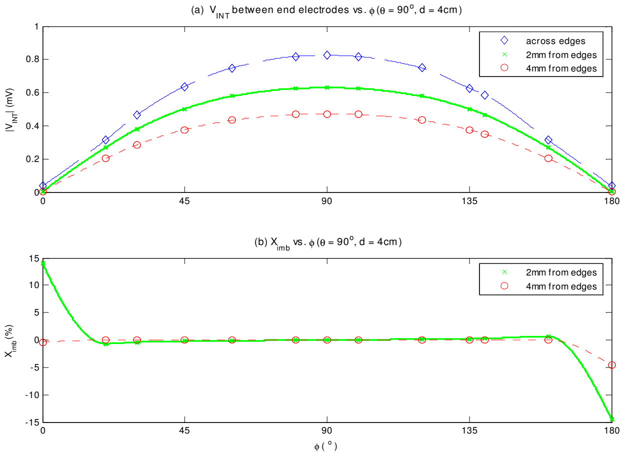


Figure 10. (a) Similar to Fig. 9a (d = 4cm) for electrodes placed at the cuff edges, at 1mm and at 2mm inside the cuff ends. (b) Corresponding imbalance variation

Similarly, in Figs 9b and 10b illustrate cuff imbalance variation with φ using Eq. (1). In the first figure end electrodes are placed at 2mm inside each end of the cuff, and a third electrode in the middle of the cuff while d is again shifted from 4cm to 7cm. In the second case the distance is kept at 4cm and the end electrodes are shifted from 2mm to 4mm inside the cuff edges. These graphs indicate clearly that both interference amplitude and imbalance vary with changes in cuff orientation.

B. *Effect of proximity on tripolar-cuff amplifiers*

The preceding figures indicate that proximity causes variations to both interference amplitude and imbalance. However, they do not reveal how the combined effect of these factors affects the performance of the TT and the QT in terms of interference feedtrhough to the output. Fig. 11 illustrates the combined effect of EMG amplitude and imbalance variation on the conventional amplifiers. The plots were generated using experimental data corresponding to Fig. 9 as inputs to ideal Matlab-Simulink® models of the QT and TT. The ENG was represented by a 1kHz, 1μV pk-pk sinusoid.

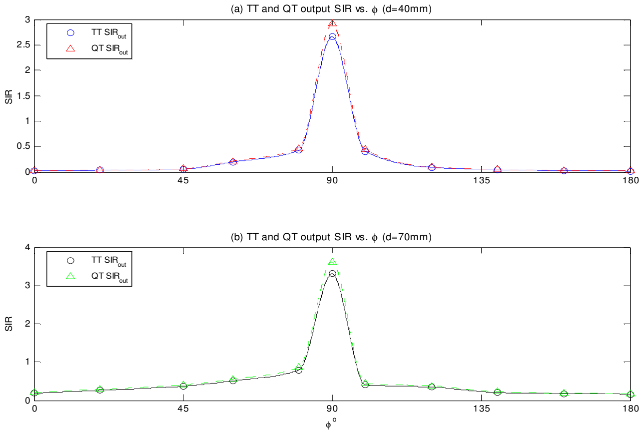


Figure 11. The effect of proximity to the output ENG:EMG ratio of TT and QT neural amplifiers, with ENG input amplitude of 1 μV pk-pk. (a) d = 40mm (b) d = 70 mm.

The results indicate that apart from values close to $\phi = 90^o$, proximity variations seriously affect the output ENG:EMG (mentioned here as signal-to-interference ratio or SIR) of both amplifiers. There is a small window of ϕ values between approximately 80° and 100° where both systems exhibit output SIR greater than 1. For the rest of the orientations the SIR is very poor and ENG measurements using these amplifier configurations would be highly degraded. A solution to this problem is offered by the AT as reported in [2,4]. SIR output for both the TT and the QT is almost stable between 0° to 45° and 135° to 180°, with values of approximately 0.05 for d = 4cm (Fig. 11a) and 0.2 for d = 7cm (Fig. 11b), respectively.

V. DISCUSSION

It is evident from the simulations that cuff imbalance is affected by the proximity of the external interference source to the cuff. The predictions from the simulations were confirmed by in-vitro experiments that indicated very similar patterns in both interference amplitude and cuff imbalance changes. In both cases, variation was observed with both distance and orientation, with the latter causing a more severe effect especially when the source dipole and the cuff are vertical to each other.

When the end-electrodes are placed close to the cuff edges, the proximity of the interference source to the cuff influences cuff imbalance more severely. This has the implication that different types of interference source (e.g., EMG and stimulus artifact during stimulation) would possess a different cuff imbalance value as observed in-vivo [1]. The results presented here are probably more significant for interference during stimulation, where two different types of interference appear, as mentioned above. It should be noted that the models here assumed homogeneous conductive medium (saline), while in reality the field lines will be disturbed by non-homogeneous tissue. Hence, further research should involve more complex models of interference source and conductive media.

Proximity variation also has a strong effect on the interference amplitude across the cuff. The greatest cuff imbalance variations were observed for the angles that caused the interference amplitude to be at a minimum.

VI. CONCLUSION

Although implant technology has advanced greatly in recent years there are still fundamental issues with regard to the neural interface itself, which have not yet been investigated. In an attempt for better understanding of the cuff neural interface, this paper has reported on a new contribution to cuff imbalance which we call “proximity imbalance”. The simulated results for this condition have been verified by saline-bath experiments.

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