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Experimental Assessment of Imbalance Conditions in a Tripolar Cuff for ENG Recordings

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Abstract- **Functional Electrical Stimulation (FES) may be improved by the use of naturally occurring nerve signals as feedback signals. However, the usefulness of the recorded electroneurogram (ENG) signals from nerve cuff electrodes depends on the amount of electromyogram (EMG) interference and stimulus artefact present. Tripolar cuff electrodes reduce interference but suffer from imbalance, which degrades the performance of amplifier recording configurations. Previously cuff imbalance has been mainly associated with impedance variations inside the cuff and cuff asymmetry. In this paper, imbalance is associated with additional factors, including cuff orientation and distance from the interference source. The findings are based on in-vivo and in-vitro experiments performed using a true-tripole amplifier recording system.**

Keywords – **Cuff imbalance, ENG recording, EMG, tripolar electrodes, true-tripole.**

I. INTRODUCTION

A major challenge in neuroprosthetics is to use naturally-occurring electroneurogram (ENG) signals to provide sensory feedback to artificial devices [1], [2]. Cuff electrodes are a stable method for long-term recording of ENG data from peripheral nerves [3]. Unfortunately, the ENG signal recorded using cuff electrodes is in the order of a few µV whereas interfering signals can have much larger amplitudes, and the spectra of the various signals overlap [4], [5]. Common sources of interference, of mV amplitudes, are the electromyogram (EMG) potentials generated by excited muscles near the cuff. Various methods have been suggested to reduce interference pick-up, mostly based on the use of multiple electrode structures within the cuff [3], [6], [7]. One of the simplest types of nerve cuff is the tripolar cuff (i.e., a split-cylinder containing three equally spaced ring electrodes embedded in the inside wall) as shown in Fig. 1.

The tripolar cuff is commonly used with the quasi-tripole (QT) or true-tripole (TT) amplifier recording configurations [6], [7]. In theory both configurations eliminate interference pick-up by taking advantage of the *linearization* property of the cuff (Fig. 1). Nevertheless, in practice their performance is degraded by the presence of cuff imbalance which was previously mainly associated with mismatches in Z_{t1} and Z_{t2} in Fig. 1 [4]. In Fig. 1 Z_{t1} and Z_{t2} represent the tissue impedances inside the cuff, Z_{t0} is the tissue impedance outside the cuff, Z_{e1}, Z_{e2} and Z_{e3} are the electrode-tissue contact impedances and I_{EMG} is the interfering EMG current that flows inside the cuff.

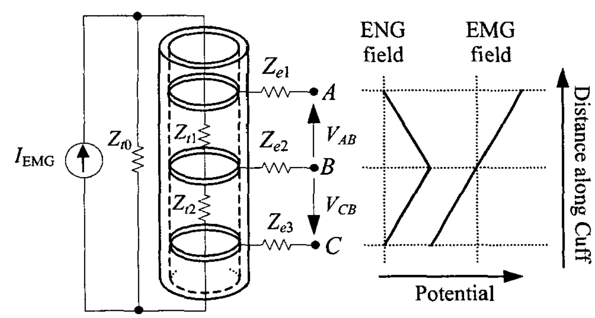

Fig. 1. Tripolar cuff impedances and linearised ENG and EMG fields (not to scale). Typical values: $Z_{t0} = 200\Omega$, $Z_{t1,3} = 2.5k\Omega$, $Z_{e1,2,3} = 1k\Omega$, $I_{EMG} = 1\mu A$.

However, there is limited information about the maximum imbalance that may occur in cuff recordings. Moreover, it is not clear how cuff imbalance relates to the position and the distance of the interference source from the cuff. For this reason, in-vivo experiments were performed to investigate whether different interfering signals result in different cuff imbalance, how cuff imbalance is affected by cuff asymmetry, and whether cuff imbalance changes by varying the distance between the cuff and the interference source.

The remainder of the paper is organized as follows: Section II describes the experimental setup and procedure and Section III presents experimental results which provide a comparison of the cuff imbalance for various conditions. Finally the results are discussed in Section IV and conclusions are drawn in Section V.

II. METHODOLOGY

A. Definition of Cuff Imbalance

In this paper cuff imbalance, X_{imb}, is expressed as follows: Say that the cuff output in Fig. 1 is solely interference and $|V_{int}| = |V_{AB}| + |V_{CB}|$, where V_{int} is the interference across the cuff. Ideally:

$$|V_{AB}| = |V_{CB}| = 50\% \, |V_{int}| \tag{1}$$

In realistic conditions:

$$|V_{AB}| = (50\% \pm X_{imb}) \, |V_{int}| \tag{2}$$

with X_{imb} having a theoretical maximum value of 50%.

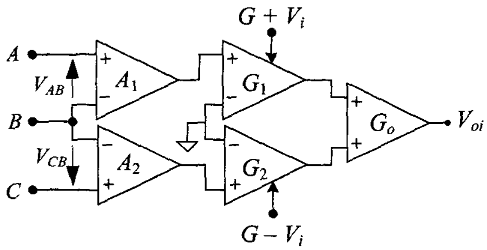

Fig. 2. Configuration of the recording amplifier.

B. Design of the Recording System

The recording system was based on the TT configuration with the addition of a variable gain stage as shown in Fig. 2. The system consisted of two low-noise preamplifiers (A_1 and A_2), two variable gain amplifiers (G_1 and G_2), and a summing output amplifier (G_o). The gains of G_1 and G_2 were $G + V_i$ and $G - V_i$ respectively, where G was fixed and V_i was manually varied through 11 steps ($i \rightarrow 1$ to 11), with step 6 giving $V_6 = 0$. This middle position gave an output V_{o6} and resulted in $G_1 = G_2 = G$ for both variable gain amplifiers.

The system was built on a printed circuit board with power supply rails of ±8V. The preamplifiers were realized using AC coupled AMP01 differential amplifiers with a bandwidth of 25kHz and a gain of 400. The variable gain amplifiers were realized using AD633 analogue multipliers with a mean gain $G = 2$, and the output stage by a summing amplifier (OPA277) with a gain $G_o = 10$ which resulted in an overall ENG signal path gain of 16000. Each of the 11 gain steps corresponded to a change in X_{imb} of 8.5%.

C. Experimental Setup

Eight sets of acute experiments were performed in six New Zealand White rabbits with weights of 3 to 3.5kg. They were anaesthetized with "rompun cocktail", first dose 5ml and subsequent hourly doses of 2ml. A split type cuff with inner diameter of 2mm and length of 22mm was used with four platinum foil ring electrodes (Fig. 3). The cuff was tripolar, with a choice of two middle electrodes (denoted E_1 and E_2) placed each side of the middle of the cuff, 2mm apart. The end electrodes were placed at 2mm from each of the cuff edges. A switch allowed the middle electrode of the tripolar cuff to be E_1, E_2 or E_1E_2, the latter option denoting that the two electrodes had shorted. The purpose of switching between the three electrode positions was to allow some manual control over the cuff asymmetry.

A second tripole cuff with inner diameter of 2mm and length of 12mm allowed the application of *bipolar* or *tripolar* stimulation. The stimulus current pulses were between 1 and 1.5mA, had a width of 200µs and a frequency of 5Hz. The stimulating cuff was placed around the sciatic nerve and the recording cuff around the tibial nerve approximately 2cm from each other (see Fig. 3).

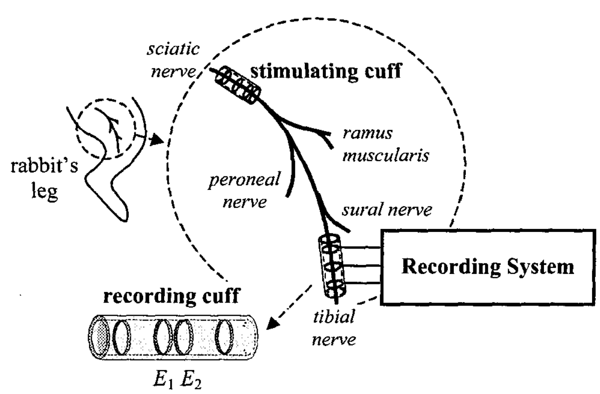

Fig. 3. Experimental setup. Illustration of the nerves involved and position of the recording and stimulation cuffs.

Initially all nerve branches shown in Fig. 3 were present. Measurements were taken for all 11 gain steps for each middle electrode option (E_1, E_2 and E_1E_2). The tests were repeated after cutting the ramus muscularis, the peroneal nerve, the tibial nerve distal to the recording cuff and finally the sciatic nerve between the two cuffs. Cutting these nerve branches changed the muscle activity, which allowed observation of how variation in the location and intensity of the interference affected the imbalance.

Measurements were recorded using a TEAC RD-145T DAT recorder with a sampling frequency of 20kHz. The interference signals present were stimulus artifact and *M*-wave. The nerve signal produced was the compound action potential (CAP) which consisted of a positive and a negative peak up to 3 orders of magnitude larger than naturally occurring ENG [5].

III. Results

Fig. 4 illustrates superimposed system outputs for all 11 gain variations (experiment number 1, E_1E_2) after ramus muscularis was cut. The graph shows that the stimulus artifact and the *M*-wave are close to zero (i.e., the corresponding imbalance is removed) for different gain values. The *M*-wave is close to zero for V_{o6} ($X_{imb} = 0$), which gives a non-zero stimulus artifact peak. The peak of the stimulus artifact becomes zero somewhere between gain steps 4 and 5 corresponding to X_{imb} between 8.5% and 17%.

By connecting the peaks of the stimulus artifact and the *M*-wave for the 11 gain values, as shown in Fig. 5a, their imbalance may be calculated by the zero crossings. In this case the imbalance of the stimulus artifact and *M*-wave were 13.1% and 2.26%, respectively. Fig.5b shows the imbalances for both interferences in all experiments.

Fig. 6 illustrates the stimulus artifact versus the *M*-wave imbalance variation, occurring with changes in the middle electrode position. The respective X_{imb} variations of the two signals were plotted against each other for all eight experiments to show whether the change affects both

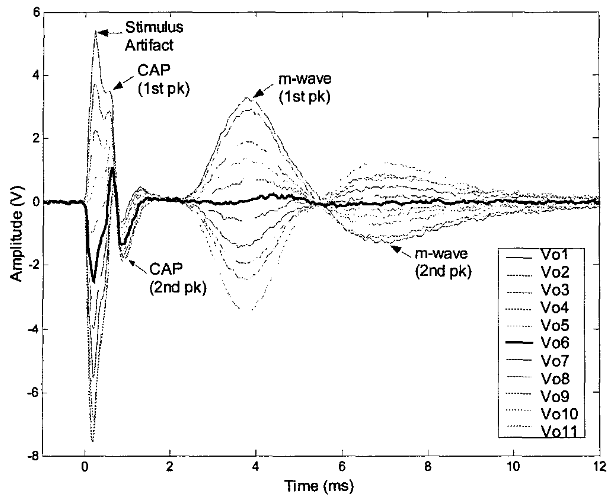

Fig. 4. Superimposed outputs for the 11 gain steps (experiment number 1, E_1E_2). The thick black line corresponds to zero imbalance and in this case gives the minimum M-wave, but not the minimum stimulus artefact.

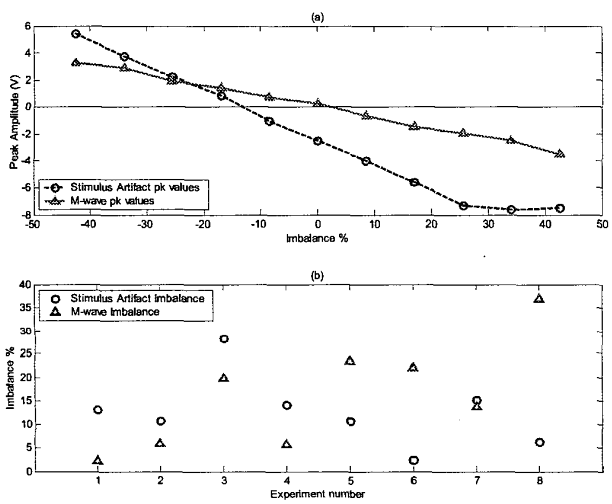

Fig. 5. a) Stimulus artefact and M-wave peaks versus X_{imb} for all 11 outputs of Fig. 4. b) Imbalances for experiments 1–8 (ramus muscularis cut).

similarly, in which case, the resulting line would have a gradient of 45°. Table I shows how the imbalance due to the M-wave was affected in each experiment after cutting the ramus muscularis, the peroneal and finally the tibial nerve. Measurements were taken using the E_1E_2 middle electrode connection.

Finally, saline-bath experiments performed indicated that a distance variation from 1cm to 2cm between the stimulating and the recording cuffs affects the imbalance by approximately 10%. The cuffs were positioned next to each other in the same direction and orientation. It was also observed that the actual amplitude of the interference is reduced with distance.

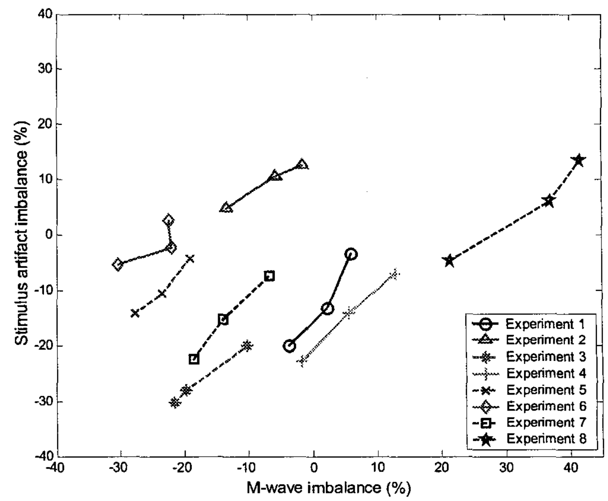

Fig. 6. Stimulus artifact imbalance variation versus M-wave X_{imb} variation when middle electrode changes between E_1-E_1E_2-E_2 (left to right).

TABLE I

M-WAVE IMBALANCE (%) WITH THE FOLLOWING NERVE BRANCHES PRESENT.

Experiment number	All nerves present	No ramus muscularis	No peroneal nerve	No tibial nerve
1		2.3	11.5	29
3	18.5	5.8	11.7	2.6
3	26	19.7	21	36.4
4	7.3	5.7	3.7	3.6
5	3.9	23.4	22.6	28.9
6	28.6	22	32.2	21.9
7	1.8	13.9	13.1	13.8
8	11.8	36.9	20.4	30.1

IV. DISCUSSION

Fig. 4 shows clearly that the CAP (the peak not covered by interference) is essentially undistorted by the gain variation of the system. The peaks of the stimulus artifact and the M-wave are gradually reduced for different gain steps, they pass from a minimum position and then they change phase. Interestingly, this position is not the same for the two interfering signals. Fig. 5a shows that within the available voltage range, the overall response of the system to the gain steps applied was approximately linear. Fig. 5b shows that in 6 out of 8 experiments the imbalance difference between the stimulus artifact and the M-wave was less than 15%.

Manually introduced asymmetry (Fig. 6) shows that although other parameters are involved, imbalance is also associated with fabrication tolerances and impedance mismatches between the two halves of the cuff. Fig. 6 illustrates the relevant effect that this asymmetry has on the two sources of interference and it shows that, in most cases, changing electrode position affects both interferences similarly.

As shown in Table I, no pattern may describe the imbalance variation after subsequently cutting the same nerve branches in each experiment. Although the average change ranges from 6% to 10.5%, in some cases the difference in imbalance reached 25%. Possible reasons for this uneven imbalance variation between experiments and nerve-cutting cases are:

- Cuff deformation when placed between muscles.
- Saline distribution inside and around cuffs.
- Different response to stimulus signal for different muscles and animals.
- Changes in distance and orientation between cuffs because of surgery each time nerves were cut.
- Cuff disturbance by some of the muscle activity
- Air bubbles inside the recording cuff (based on saline-bath experiment observations).
- Imperfect and imbalanced cuff closure.

The ramus muscularis was the branch more obviously affecting the measurements in terms of unwanted cuff movement by muscle activity, since it affected the muscle closer to the recording cuff and it resulted in more intense leg movement than the other branches involved. Finally, it was observed that imbalance is affected by variation in the distance and orientation of the recording cuff relative to the interference source.

V. Conclusion

The imbalance of a tripolar cuff varies for different sources of interference. In this paper this was observed for stimulus artifact and *M*-wave over eight experiments, which showed an average difference of 12% and a maximum difference of 30%. The imbalance of the *M*-wave may depend on which muscles are active. Changes up to 25% have been observed, although some of the difference may have been introduced by accidental cuff position variation. Changes in the cuff geometry had the expected effect in the imbalance and affected both interfering signals similarly, with variations of 5 to 10%. The recording cuff orientation and distance from the interference source is another factor that affects the imbalance. Based on the observations made, the electric field of an external source of interference will probably be more uniform inside the cuff as the source moves away from it and/or towards the middle electrode plane.

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